TOWARDS AUTOMATED GUIDANCE FOR HELPING NOVICES DESIGN FOR SUSTAINABLE ADDITIVE MANUFACTURING AND CNC MACHINING

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Ruoyu Song

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TOWARDS AUTOMATED GUIDANCE FOR HELPING NOVICES DESIGN FOR SUSTAINABLE ADDITIVE MANUFACTURING AND CNC MACHINING

Approved by:

Dr. Cassandra Telenko, Advisor
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Christopher Saldana
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Frank Durso
School of Psychology
Georgia Institute of Technology

Dr. Yan Wang
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Thomas Kurfess
School of Mechanical Engineering
Georgia Institute of Technology

Date Approved: May 16, 2019

To my husband, family and friends

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LIST OF SYMBOLS AND ABBREVIATIONS

CAD	computer-aided design
CAM	computer-aided manufacturing
CAPP	computer-aided process planning
AM	additive manufacturing
SM	subtractive manufacturing
DFM	design for manufacturing
FDM	fused deposition modeling
CNC	computer numerical control
SLS	selective laser sintering
LCI	life cycle inventory
P	number of users
T	environmental cost of manufacturing technology
I	overall environment impact
A	affluence, the average consumption of each person in the population
Y	dependent variable
b_i	coefficients
X_i	Independent variables
m_{waste}	wasted mass
$m_{inv_{\mathrm{i}}}$	initial filament inventory
m_{inv_f}	ending filament inventory
m_{order}	ordered filament
m_{usage}	used filament

$m_{printed}$	mass removed from makerspace
R_{waste}	rate of material waste
R_{usage}	rate of material usage
r_{scrap}	scrap ratio per collection period
$r_{avgcrap}$	overall average scrap ratio
d_{sample}	length of collection period
d_{supply}	days in each inventory check period
EI_{print}	printing energy intensity
EI_{use}	overall use energy intensity
P_{print}	average printing power
P_{idle}	average idle power
$P_{preheat}$	average preheating power
t_{print}	printing time per print
$t_{preheat}$	preheating time per print
t_{idle}	average idle time per print

SUMMARY

Thanks to computer-aided design (CAD) and computer-aided manufacturing (CAM) software, novice engineering designers can engage in product design and production more easily, increasing opportunities for innovation. Despite this increase in computer support, novice designers still make improper design decisions which unnecessarily increase the fabrication failures that lead to higher environmental impacts. For fused deposition modeling, the baseline waste rate for material consumption was 35-45% which increased the energy usage by 45%. Therefore, this research aims to discover what feedback content should be provided to novice designers, and what strategies best communicate the content. The feedback content and strategies were developed from existing databases, benchmarking studies, interviews and observation studies in a university machining mall. The feedback content identified includes the design for manufacturing guidelines and design suggestions to inform novice designers about how to make changes to fix problems with their designs. The effective strategies identified include visualization of problematic features by highlighting the features and providing example pictures to show high and low manufacturability features. A novice DFM prototype was developed and tested. From the test, the prototype was able to assist novice designers better than the benchmarking software, in terms of average number of problems identified and fixed, and average time spent. For the pawn piece used for the testing, the novice prototype could assist the participants to identify 0.97 ± 0.05 problems, and fix 0.94 ± 0.06 problems. When using the benchmarking software, the participants only identified 0.78 ± 0.12 problems, and fixed 0.70 ± 0.13 problems.

CHAPTER 1. INTRODUCTION

1.1 Research Motivation

Thanks to computer-aided design (CAD) and computer-aided manufacturing (CAM) software, novice engineering designers can engage in product design and production more easily, increasing opportunities for innovation. The designers can easily create models in CAD software and produced it using rapid prototyping tools such as 3D printers. However, there is no developed system which can automate the entire process from design to manufacturing. Designers need to use different software tools for each stage of the product development process and make decisions without guidance, which could increase the failure risks for the product development. Therefore, fully automated CAD-CAM software system will be developed to enable individuals at different expertise level to engage in product design and production. This system will provide feedback on geometries, tolerances, material selections to designers to assist the designers to develop parts with minimum risk of fabrication failures. With created parts from designers, this system will be able to generate manufacturing process planning automatically.

In order to develop this software system, advanced methodologies such as machine learning will be adopted in order to handle complex geometries, provide feedback and generate the manufacturing plans. In addition, this software system will consider the barriers between designers and manufacturers. Human factor research will be conducted to identify the cognitive and knowledge differences between the designers and manufacturers. By implementing the findings, the system is expected to account the differences and adjust output between designers and manufacturers.

The definitions of a novice vary greatly [1]. This study focuses in mechanical design. Novice engineering designers are usually at an early stage of mechanical design training. They have started to explore mechanical design activities using CAD and CAM software and have intentions to design and fabricate mechanical parts or systems. However, they do not have significant domain knowledge in mechanical design and manufacturing. Their knowledge is organized in casual networks [2]. These novice designers are inexperienced in design and are poised to accumulate expertise experience and knowledge [3]. When solving design problems, they tend to focus on the surface-level features when starting the design process [4–7], and the process is slow and error-prone [2].

Knowledge gaps existing prevents the development of the CAD-CAM software system. Firstly, there is no developed comprehensive algorithm to provide feedback for important parameters such as tolerance values, material selection, etc. Existing software tools can only provide feedback for part geometries, monetary cost and estimated lead time [8,9]. Secondly, the manufacturing process selection is not automated. Current manufacturing analysis systems are restricted to single manufacturing process [10]. Lastly, current software tools are not designed for novice designers. Novice designers and DFM experts are different in cognition, knowledge level and communication experiences. For example, novice designers do not understand manufacturing processes as experts do. Therefore, they may encounter difficulties in understanding the terminologies used in feedback. Experts usually operate faster and more efficiently than novices [4,11,12]. In addition, the rate of cognitive activity in novices tends to start at a peak and then decrease continuously; the rate of experts increases throughout the whole design process [13].

This study focuses on the last knowledge gap to provide feedback to novice designers. Despite the increase in computational support, novice designers still make improper design decisions. Novices use trial-and-error in design, due to their limited experience and evaluation ability [4,12,14]. Failures may be useful in education since they can help novices to better understand the structures and constraints of problems [15]. However, beginners in engineering design can experience failures in making as demoralizing [16]. Therefore, beginning practitioners and students could become hesitant to participate in design activities, which decreases the opportunity for innovation.

In addition, novice designers' improper design decisions can unnecessarily increase manufacturing costs and fabrication failures that lead to higher environmental impacts. For example, the material waste rates of additive manufacturing (AM) in university makerspaces range from 35% to 45%, which increase the life cycle energy costs by 50% or more [17,18]. The number of users, P, is increasing; as such, mistakes by these additional novice users also increase, leading to greater environmental cost of manufacturing technology, T. These two factors contribute to the overall environment impact, I, represented conceptually in the IPAT equation [19], shown in Equation 1.

$$I = P \times A \times T \tag{1}$$

Even if A, which represents the average consumption of each person in the population, is assumed to be constant, the environmental impacts increase for CAM. The most viable way to reduce impacts is by addressing the technological impacts, T. The goal of this research is to develop a new CAD-CAM software system to decrease technological impacts of CAM technologies by helping novice engineers minimize material waste and energy loss in automated manufacturing processes. This system should be able to provide design feedback to novices in design for manufacturing to assist in design of mechanical parts or systems.

In order to provide feedback automatically for novices, feedback content and strategies are identified from this work. The feedback content is the information provided to the users, with the feedback strategy is the way to provide the information. There are two sources of feedback content: lists of design for manufacturing (DFM) guidelines and freeform design suggestions given by manufacturers. Novice engineering designers ignore constraints [20], and consider fewer criteria during the design process than designers with more expertise [21]. Therefore, their designed parts may not be realizable [20]. Novice designers tend to follow guidelines that are decomposed into context-free features by experts [22]. Design guidelines impact how designers perceive and frame the design task, evaluate ideas and complete their projects [23]. However, novices may apply rules without evaluating the applicability to the design problem critically [24]. Hence, novices often need to solicit help from external sources to apply guidelines and perform design activities effectively. Guidelines are general rules and principles for the design of all parts. DFM guidelines for conventional manufacturing processes have been well developed [25–29], and can be provided by software analyzing parts automatically. To provide the feedback, manufacturability of the part needs to be analyzed.

For feedback strategies, manufacturers could provide feedback to novice designers to assist them in making design decisions, but often lack the time required to bridge the knowledge gap between them (the manufacturer) and the novice designer. Novices tend to treat design as a linear order set of strategies instead of an iterative process [1]. Novices are unable to evaluate designs before testing them due to their limited experience and ability [4,12,14]. In addition, novices tend to be hesitant to ask for recommendations and help from other people [12]. Therefore, a feedback system could be developed to assist designers and improve the product manufacturability before engaging manufacturers [30].

From the identified feedback content and strategies, an automated DFM software tool will be developed to assist novice designers make design decisions with minimized fabrication failure risks. This automated DFM software tool will be a fundamental part for the overall CAD-CAM software system.

1.2 Research Hypothesis

> Feedback content, including DFM guidelines and design suggestions, and feedback strategies, including visualizations and strategies used by human experts, can effectively decrease the fabrication failures of CAM technologies by assisting novice engineering designers to make better design decisions.

This hypothesis addresses two primary goals of this research. The first goal is to identify the feedback content for novice engineering designers. This research proposes to provide feedback content, including DFM guidelines and design suggestions, to assist novice designers to make better design decisions using automated software. The feedback content was extracted from existing databases and combined with new guidelines and design suggestions found through interview and observation studies of novice designers and manufacturers. The second goal is to identify effective feedback strategies to provide feedback to novices on their designs. The feedback strategy was developed from benchmarking studies and observations of communications between machinists and designers in a university machine shop.

The long-term goal of this work is to develop new CAD-CAM software systems that reduce the load on human experts and decrease environmental impacts of CAM technologies used by novice designers. The developed feedback content and strategies will be used to develop an automated software tool to reduce burden on human experts. Human experts can provide feedback to novice designers to assist them to make design decisions more effectively, but often do not because of knowledge gap and time required. Therefore, this automated DFM software tool could reduce burden on the human experts and provide feedback effectively.

1.3 Research Scope

This research investigates CAM technologies including additive manufacturing (AM) and subtractive manufacturing (SM). AM and SM could be integrated in the future, since they share characteristics and can take digital CAD models as inputs [31]; both manufacturing processes and process planning of AM and SM could be automated [32]. For AM, fused deposition modeling (FDM) was investigated. For SM, computer numeric control (CNC) machining was investigated. Both FDM and CNC machining use 3D CAD files as input. With the assistance of CAM software systems, a printing path or tool path can be generated for FDM and CNC machining, respectively. By using these CAM technologies, prototyping and fabrication becomes easier and more accessible for novice engineering designers. Hybrid CNC machines that integrate AM and SM have been developed [33]. Therefore, the findings from either FDM or CNC machining could be easily applied to the other.

This dissertation encompasses two main research questions, addressing the goals of this study.

RQ1. What feedback content should be provided to assist novice engineering designers to make design decisions to decrease environmental impacts of CAM technologies?

RQ2. What feedback strategies should be used to provide the feedback content?

1.3.1 RQ1: What feedback content should be provided?

Feedback content should be provided to novices to assist them in making design decisions in order to decrease fabrication failures. Manufacturing feedback can provide redesign opportunities to designers in order to reduce the number of design iterations [34]. This research question addresses the need to identify what feedback content can assist novices effectively and efficiently.

DFM guidelines are the most common type of manufacturability feedback. Novice designers prefer to follow rules developed by experts [22]. The existing software, such as DFMXpress and Xometry, provides DFM guidelines for identified problematic features. DFM guidelines are well developed for conventional manufacturing, such as SM. However, DFM guidelines for AM are still under development. Many studies have developed guidelines for specific AM process. However, these guidelines are not well integrated like SM. Therefore, existing guidelines should be well combined into a comprehensive design guide. In addition, most existing guidelines involve terminologies that novice designers are not familiar with. Therefore, novices may be hesitant to use these guidelines. Hence, current DFM guidelines should be modified to match the knowledge space of novice designers.

In addition, Kim identified that existing guidelines are at different levels, such as “preferred” vs. “should not be violated” or “normal” vs. “tight” for the same manufacturing process and geometric parameters [35]. He stated that it is important to identify and improve the features with more serious problems that at higher risk of failure in order to avoid further alterations. Therefore, it is essential to figure out what guidelines are most serious and important for novice designers. To identify the most serious and important guidelines, common failure reasons for parts designed by novices should be identified.

In addition to DFM guidelines, other feedback content that has potential value to novice designers should be identified and evaluated. Current systems, such as Xometry, provide feedback on estimated monetary cost and lead time on designed parts. However, studies should be done to evaluate how effectively these types of feedback can help designers. In addition, feedback content that is not implemented in existing software systems should be evaluated. For example, Binnard and Cutkosky developed a primitive-based approach to provide feedback on the manufacturing process for designers [36].

1.3.2 RQ2: What feedback strategies should be used?

Research question 2 addresses the need to identify and implement effective feedback strategies used by human experts and existing computer software.

Implementing a part visualization can assist the designers, since it can enhance the user's perception of shapes and structures of products [37]. It can also display design alternatives and assist designers more effectively in early design stage [38–40]. Visualization of features delivers information in higher detail and more effectively than text descriptions [41]. Therefore, using visualization techniques, such as drawings and CAD models, is good strategy to provide feedback.

The primary forms of communication between a designer and a manufacturer is drawings and CAD models. However, the drawings and models may be misinterpreted because of the different perspectives of different viewers [42–44]. Face-to-face communication using gestures and oral communication could be used to supplement the drawings and model [45]. However, it is difficult and costly due to the increasingly global nature of production. Therefore, automated systems should be developed to replace the face-to-face communication. Existing systems did not consider the limitations of human cognition and expertise differences across product development [46–48]. Therefore, the computer system needs to provide easy-to-understand information to novice designers by matching the cognition and expertise space of novices.

Effective strategies to adjust the DFM experts' knowledge for novice designers could be identified by observing the communication between novice designers and manufacturers who are experts in assisting novices. The manufacturers observed were machinists in a university machine shop. They review manufacturing requests submitted by students from different majors in the university, provide design feedback based on the submitted drawings or CAD models, and manufacture these parts for students. Their expertise in assisting novices has been developed through experience [49,50]. The experts are able to recognize underlying principles easily when solving a design problem [4–7,51], and develop “rules of thumb” to simplify solutions [52]. Therefore, observing this group of machinists can identify the effective approaches they use to assist novices.

In addition, the usability of the system should be considered when implementing feedback strategies. If a feedback strategy tends to decrease the usability of the system, it should be carefully considered before implementing into the computational support system.

1.3.3 Research Tasks

Three main tasks were completed to answer these two research questions. Figure 1 shows the research roadmap.

Research Task 1: Collect data related to feedback for CAM technologies from literature review, benchmarking studies, observations and interviews of designers and machinists in university makerspaces.

Research Task 2: Process collected data to identify feedback content and strategies for novices.

Research Task 3: Evaluate the findings by developing and testing a software prototype.

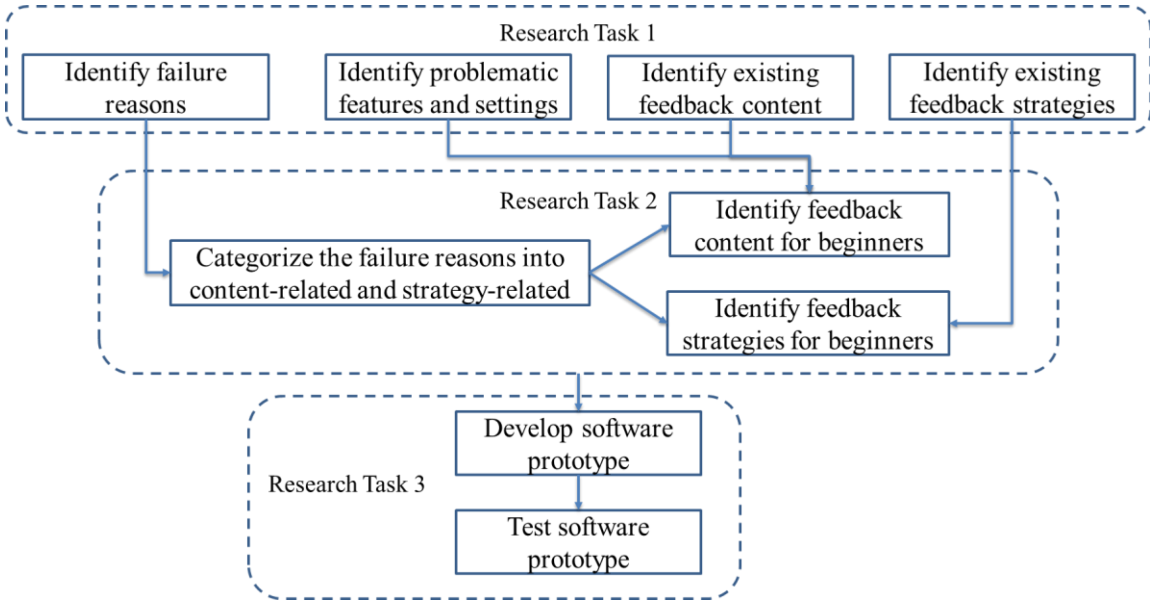


Figure 1 - Research Roadmap

1.4 Organization

This dissertation presents three main components of research: (1) motivating studies to develop automated guidance for novice engineering designers to make design decisions, (2) studies to identify failure reasons and communication problems for CAM technologies, (3) validating the findings by building and testing the prototype.

Chapter 2 presents background information and literature review regarding environmental impacts of CAM processes, fabrication failures of CAM process, DFM guidelines, automated DFM approaches and methodologies, and experience/expertise level of designers. Chapter 3 presents detailed analysis of environmental impacts of fabrication failures of FDM[1]. Chapters 2 and 3 highlight the importance of studying fabrication failures of CAM processes and the demand for DFM software for novices.

Chapter 4 presents the causes for failures in desktop FDM to reduce fabrication failures of desktop FDM. Chapter 5 presents the causes for failures in CNC machining and communication problems between machinist and designers. These two chapters identify failure reasons and communication problems for CAM technologies.

Chapter 6 combines the findings in previous chapters to build the DFM prototype for novices. It summarizes the limitations of existing systems and develops improved feedback content and strategies. Finally, Chapter 7 presents the test results of the prototype. Chapter 8 concludes the dissertation with a summary of contributions, limitations and future work.

[1] Chapter 3 has been published as [17,18]

CHAPTER 2. LITERATURE REVIEW

This chapter reviews the studies of environmental impacts, fabrication failures, current DFM guidelines, and automated feedback strategies for both additive manufacturing (AM) and subtractive manufacturing (SM), communication between designers and manufacturers, and the effects of expertise level of designers on their cognition and design outcomes.

The literature review shows that fabrication failures could have significant influences on the total environmental impacts. However, only a few studies focus on fabrication failures. In order to decrease fabrication failures, DFM guidelines should be used for CAM processes. DFM guidelines are well developed for conventional manufacturing. However, design for AM guidelines are still in development. In addition, software systems should also be developed to assist the decision-making process for design. Automated DFM approaches and methods are developed mostly for conventional manufacturing processes. Few studies consider the improvement of manufacturability for AM.

Moreover, existing literature discusses designers' expertise levels. However, few studies have been done to evaluate expertise differences of DFM novices and experts, and how to accommodate these differences to assist them to communicate in a more effective and efficient way.

2.1 Environmental impacts of CAM processes

Manufacturing activities significantly influence the environment. In 2006, the manufacturing sector accounted for 12.3% of industry gross domestic product, but were attributed with 36% of carbon dioxide emissions within the industrial sector in US [53]. Manufacturing output was also responsible for 84% of energy related carbon dioxide emissions and 90% of the energy consumption in the industrial sector [54]. Making design decisions that facilitate sustainable manufacturing is highly desirable [55]. Achieving manufacturing sustainability requires a holistic view for planning the entire product life cycle, including manufacturing [56].

For subtractive manufacturing (SM), such as milling and turning processes, the energy consumption results over 99% of the environmental impact of the machine [57]. Li and Kara developed an empirical model to predict energy consumption of turning process. This energy consumption estimation model was based on manufacturing process factors, such as the tool condition, workpiece material, cutting parameters and cutting fluids.

The energy consumption sources of mechanical processes are divided into two parts: energy of auxiliary machine movements and intrinsic process movements. Considering data sources, there are two kinds of data acquisition methods: acquiring data from a database or acquiring data from CAM files [58]. Overcash et al. produced an engineering rule-of-practice-based analysis of separate unit manufacturing process. This unit process life cycle inventory methodology was built on the principle that a manufacturing line for any given parts was as a set of unit processes to convert the inputs to the output products. This report presented the models and approaches for the unit process life cycle inventory methodology and used drilling unit operation as a case study. It calculated the time, power and energy per hole of drilling [59]. Seow and Rahimifard developed an embodied product energy framework to estimate the energy consumption of a unit product, which could provide the energy consumption in kJ for each part based on the design [60].

When evaluating the environmental impacts of AM, most studies focused on energy use [61–64]. Telenko and Seepersad estimated the energy consumption of selective laser sintering (SLS) from life cycle inventories (LCIs) and compared it to injection molding [64]. The results indicated that manufacturers could reduce energy consumption by using SLS for small production volumes. Kreiger and Pearce did a cradle-to-grave life cycle analysis of 3D printers, showed that 3D printers require less cumulative energy when products made from PLA and ABS decrease the fill percentage to below 0.79 [62]. Baumers et al. developed a tool for the estimation of process energy flows and costs occurring in the AM technology variant of direct metal laser sintering [65]. Mognol et al. studied the influence of the various parameters for several rapid prototyping systems [63]. Song et al. developed a new manufacturing energy consumption estimation approach using machine learning [66]. This framework provided a convenient approach for designers to estimate the manufacturing energy consumption during the design phase. CAD models are the major inputs for prediction of environmental impact.

The printing time is the most important parameter; the electrical energy consumption is directly dependent on the duration of the job. In addition, minimizing the volume of support material could also minimize the energy consumption for FDM. Faludi et al. found that the sustainability of AM depends primarily on the utilization, and then on the specific machines [67]. Their study also showed that the best way to optimize ecological impact per job is by maximizing printer usage, and the best strategy for sustainable prototyping is to share printers, to have the fewest number of machines running the most jobs they can.

2.2 Fabrication Failures of CAM processes

Fabrication failures can have significant impacts of the total building costs. The breakdown of a single CNC lathe may halt the entire production process leading to expensive repairs as a result of breakdown [68]. From Keller et al.'s study, the ready to use time of CNC machines studied is in the range of 82% to 85% of the total studied time. About two thirds of the total system down time is due to non-active repair times. Wang et al. listed the failure mode of the machining process with a histogram by collecting field failure data [69]. According to You and Pham, about 70% of the total failures occurred in the CNC system hardware and the other 30% occurred in the CNC system software and machine tools themselves. Their research also showed the CNC system failure position proportion and fault model proportion [70].

For AM, few studies have looked at the potential material consumption and build failures under consumer operating conditions. Most studies only consider the material and energy costs under ideal conditions. However, consumer usage could have large material impact for some products. For example, the scrap production in conventional machining ranges from 10% to 60% [71]. Therefore, the actual material waste is dependent on operating conditions and consumer usage. Under ideal conditions, Xu et al. considered two quantities of material consumed by FDM: the amount of material used to build the part and the amount of material used to build the support. Failed parts were not considered [72]. Telenko and Seepersad mentioned failed builds as part of the material waste, but did not measure waste material [64]. Song et al. investigated the energy and material consumption considering fabrication failures of desktop FDM in university makerspaces, which shows that the baseline waste rate is 35-45% [17]. For the energy consumption, the energy intensity range is 127.27-288.41 MJ/kg for 95% confidence, if considering fabrication failures. The details of this research are shown in Chapter 3.

Some studies investigate the influence of processing parameters on AM. Alafaghani et al. investigated the independent effect of each processing parameter on the mechanical properties and dimensional accuracy repeatability of FDM parts [73]. The study shows that the dimensional accuracy is affected by build orientation, extrusion temperature, and layer height more than infill percentage, infill pattern, and printing speed. Mechanical properties of parts are influenced significantly building orientation, extrusion temperature, and layer height; and less significantly on infill patterns and printing speed.

Onwubolu and Rayegani investigated the effects of five important process parameters on the tensile strength of test specimen: layer thickness, part orientation, raster angle, raster width, and air gap, using design of experiments [74]. Minimum layer thickness improves tensile strength, but increases the material usage. Negative air gap, minimum raster width and increased raster angle improve the tensile strength. Maximum tensile strength can be obtained when the part orientation coincides with the direction of tensile loading.

The relationships between design parameters and 3D print build failures are being explored by a few researchers. Seepersad et al. created a designer's guide for dimensioning and tolerancing selective laser sintering (SLS) parts [75]. Several online user guides discuss common problems and solutions for commercial FDM printers [76–78]. All3dp.com detailed 34 of the most common FDM problems with a series of recommended solutions [76]. Print Quality Troubleshooting Guide compiled an extensive list of the common 3D printing issues with a large collection of real-world images [77]. RepRap.org provided a print troubleshooting pictorial guide to identify and resolve issues for RepRap 3D printers [78]. These resources illustrate the numerous and frequent errors that occur in AM, but the frequency of such errors and various user and machine interactions leading to such errors have not been studied.

The actual material waste of 3D printing is larger than that predicted by studies using ideal operating conditions without human or printer error [18]. Baumers and Holweg studied the cost impact of the risk of build failure in laser sintering and found that the expected cost impact of build failures was responsible for up to 38% of total cost [79].

2.3 DFM Guidelines

DFM guidelines should be used to decrease the environmental impacts and fabrication failures of CAM processes. For conventional manufacturing including machining, DFM guidelines are well developed [26–29]. However, design for AM guidelines are still in development.

AM provides design freedoms in four categories: shape complexity, hierarchical complexity, material complexity, and functional complexity [80]. AM can reduce the number of parts and eliminate fasteners, which can reduce assembly time, cost and difficulties in assembly [81]. Hopkinson et al. found that AM can reduce the environmental burden and disassembly cost using part redesign without applying any design rules [82].

Mansour and Hague investigated the impact of rapid manufacturing techniques on the design process and the product development cycle, and concluded that rapid manufacturing processes can accommodate all the established DFM guidelines easily [83]. However, conventional DFM fails to match the advantages provided by AM [81]. Many studies have been done to develop design for AM guidelines for general and specific AM processes [75,84–89]. Rosen discussed the past, present and future directions of DfAM, and stated the objective that DfAM should be used to maximize product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies [90]. Becker et al. introduced some general principles for the design of rapidly manufactured parts [84]. Some of the important design rules are:

- "Do not build the same parts as other processes. Take the time to rethink the whole assembly, reduce it to the functionality and then go straight forward to the integrated freeform design."

- “Reduce the number of parts in the assemblies by intelligent integration of functions.”
- “Feel free to use freeform designs; they are no longer difficult to produce.”
- “Optimize your design towards highest strength and lowest weight.”

Atzeni et al. identified the redesign guidelines and cost model from an extended literature review [85]. For DfAM, many studies have evaluated the influence of part printing orientation and how to optimize it. Part orientation can affect the amount of support material, printing time, part accuracy and surface roughness of the print [91,92]. An optimal orientation should be able to improve part accuracy, reduce the production time, minimize the supports needed for building the model, minimize the “poor” features, and maximize the “good” features [91].

Many studies have been done to determine the optimal orientation of AM parts [72,91,93–95]. The amount of material needed to build the support can be influenced by the part orientation [96,97]. The scrap weight can be reduced dramatically with a change in printing orientation. From the study by Alexander et al., the scrap weight of optimal orientations are only 10% and 22% of the weight of worst orientations for two different parts [96]. Reducing the amount of scrap during manufacturing saves money on material costs and waste disposal [98].

For FDM, Lieneke et al. derived dimensional tolerances of FDM through experimental investigation [40]. The results show that the average deviations range between +0.03 mm and +0.50 mm in the x alignment, between +0.06 mm to -0.30 mm in the y alignment, and between +0.12 mm and +0.47 mm in the z alignment.

Guidelines for specific AM processes have been developed. Thomas developed the design rules for selective laser melting using experimental methods. The part orientation, fundamental geometries and compound design features were studies to generate the rules [86]. Seepersad et al. determined the limiting feature sizes of various types of features including slits, holes, letters, mating gears and shafts for SLS through a series of experiments [75]. Adam and Zimmer studied design rules for laser sintering, laser melting and DFM, which totally focused on geometry. However, the developed design rules are only valid for the considered boundary conditions [87]. Lieneke et al. derived dimensional tolerances of FDM through experimental investigation [88].

However, these DFM guidelines require designers to understand the manufacturing processes [81]. Increasing numbers of novice engineering designers can access AM. However, they do not have knowledge of AM processes and DfAM. Booth et al. found that useful DfAM guidelines were proposed, but few of them were written in a way that is accessible to novice users [89]. Their research provided a visual DfAM worksheet for novice and intermittent users. It considers the complexity, functionality, material removal, and unsupported features that the model in question has. The worksheet allows the user to better identify potential failure points by adding up features on a point scale that tells them whether they should 'consider redesign'.

Besides the DFM guidelines, design for environment (DFE) guidelines have been developed for sustainable manufacturing. DFE guidelines have been developed from a number of studies [99–106]. For manufacturing, these guidelines are primarily used to assist material selection, process selection and process parameter optimization. However, the complexities of real production systems and DFE guidelines are disconnected, which creates challenges in implementing the guidelines in practice [107].

2.4 Communication between Designers and Manufacturers

Manufacturers can provide feedback, including DFM guidelines, to assist designers in making design decisions. Therefore, the communication between designers and manufacturers should be studied.

Drawings and CAD models are primary forms of communication between a designer and a manufacturer. Product development benefits from concurrent communication between designers and manufacturers to identify costly decisions, but models passed or shared between designers and manufacturers may be misinterpreted due to the differing perspectives of these viewers [42–44]. Additional layers, such as notations, are added to the drawings to communicate key information, and these notations vary from formal Geometric Dimensioning and Tolerancing (GD&T) to informal rationale and records [108].

Gestures and oral communication are also used to supplement drawings and notations [45]. These additional forms of communication, however, can be costly or difficult due to the increasingly global nature of production. To aid the process of communication through these artifacts and to develop the next generation of collaborative design tools [48], it would be helpful to understand how a common representation is interpreted differently by designers and manufacturers. Differences in interpretation can result in mistakes or miscommunication in the design or processing stages of development.

The next generation of CAD systems aim to increase sharing of part models by designers and manufacturers so that both can contribute to the design of the shape. If manufacturers and designers work together earlier in the process, they can significantly reduce costs and improve quality [109,110]. Real-time collaboration is achieved by sharing a single representation across multiple users and integrating CAD with computer aided process planning (CAPP) and CAM systems. Next-generation integrated CAD/CAPP/CAM systems and cloud based design and manufacturing systems promise to improve data and information flows within and across enterprises, but developers have yet to consider the limitations of human cognition and expertise across product development [46–48].

In this future of collaborative work, the 3D CAD models can be treated as a "boundary object", an object that has constant characteristics but may be interpreted or used differently by various parties due to their expertise or aims [111]. Eckert and Boujut stress that compatible (not identical) interpretations of boundary objects, such as part drawings, are necessary for effective design communication [112]. A CAD/CAM/CAPP system becomes incompatible when it does not match how each party works and thinks [113]. Many of these systems do not fully account for how a single 3D CAD model can be utilized in different functional settings and acts of sensemaking [114]. The manufacturer does not always need to understand the function, and the designer does not always need to understand the manufacturing process. However, they must establish a common ground to collaborate. Lang, Dickinson and Buchal found that more integration of human factors and cognitive theory is needed to understand how different parties understand design intent, history, and rationale [115]. Current efforts to address interpretation rely on incorporating annotation capabilities in models [116]. These annotations and information-based approaches, however, rely on predicting what might be misinterpreted or needed by viewers later in the product development process.

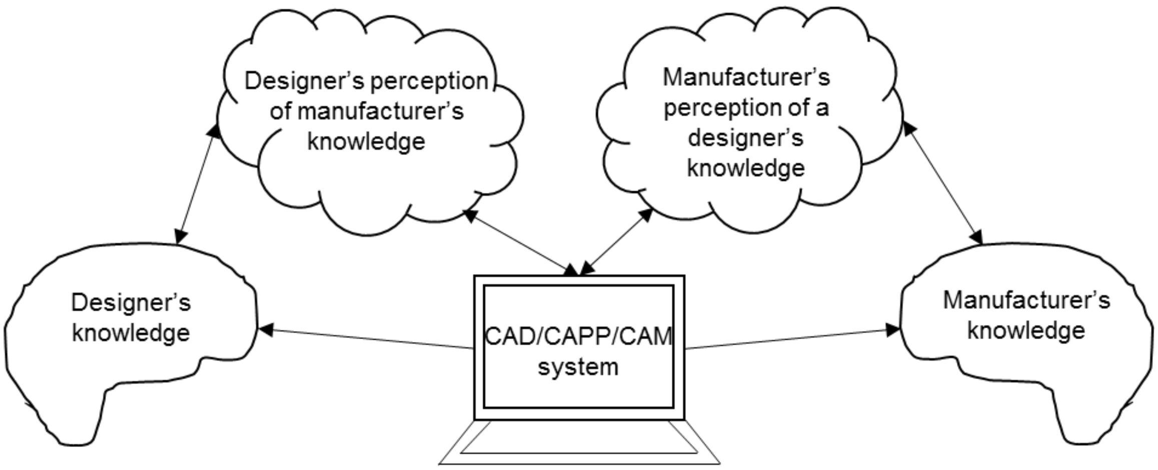


Figure 2 - CAD/CAM/CAPP systems can account for cognitive differences across product development actors

In order to support collaborative work, the CAD/CAM/CAPP system will likely need to make assumptions about how each party thinks that are more accurate than current systems. According to Nickerson's theory of communication, illustrated for the case of CAD/CAPP/CAM in Figure 2 [117], each party (i.e. manufacturers and designers) begins with a model of his or her own knowledge and translates that to fit a model of what they perceive another party's knowledge to be. Similarly, the CAD/CAM/CAPP systems impute knowledge from one party and then adjust that knowledge using its own models of the two parties [117]. Therefore, the computer system needs to have more accurate models of designer and manufacturing knowledge and adjust output between the two.

2.5 Automated DFM Approaches and Methodologies

Software systems should be developed to assist the decision-making process. Denkena et al. presents an overview of the CAPP filed, which highlighted the knowledge and collaboration gap between designers and manufacturers, and the lack of appropriate software tools to support this collaboration [118].

A systematic feedback system could improve the product manufacturability [30]. A systematic and structured complementary feedback process has been implemented by Molcho et al. to close the knowledge gap between manufacturer and designer [30]. This structured organizational learning, in the form of structured digital forms and interviews, enables maximum knowledge capture and capitalization, and is required to close the knowledge loop.

Hoque et al. developed a system that provided an intelligent interface between design and manufacturing data by developing a library of features [119]. The library linked with commercial CAD/CAM software package through a toolkit. Ferrer et al. proposed an DFM approach which combines DFM techniques and principles of Axiomatic Design [120]. They concluded that software support can improve the design process and help the designer make decisions. Wu et al. did a review of cloud-based digital design and manufacturing software and services, which provided a technology guide for decision makers to select suitable software and services as alternatives to existing in-house resources [121].

The use of annotated models is a valuable approach to improve design intent communication. Graphic user interfaces that are customized to expertise increase the accessibility of information [116]. Part visualization can enhance the user's perception of shapes and structures of products [37]. It can also present design alternatives and assist designers more effectively in the early design stage [38–40]. Visualization of features delivers information in more detail and more effectively than text descriptions [41]. Visual analytic tools are also used to support the decision-making process in manufacturing [122]. Visual analytics is defined as the science of analytical reasoning facilitated by interactive visual interfaces [123]. These tools are mostly developed for production management and supply chain decision making. Tiscsoft can optimize transportation infrastructure in supply chain networks [124]. ViSER implements two mutually coordinated panes to represent a product architecture graph and a supply chain tree [125]. ViDX can assist users to identify disruption, such as significant energy consumption of processes in a production facility [126]. However, these visual analytics tools rarely support decision-making through the entire life cycle [122]. Therefore, Ramanujan et al. proposed a visual analytics framework to generate contextual design for environment principles in sustainable manufacturing [122].

For automated DfAM methodologies, most of the systems rely on CAD models. Rosen proposed a comprehensive DfAM system considering part and specification modeling, process planning and manufacturing simulation [127]. Kumke et al. classified DfAM research into "DfAM in the strict sense" and "DfAM in the broad sense", and developed a new DfAM framework that can provide designers with structured guidelines to fully exploit AM potential [128]. Maidin et al. developed a digital design feature database to aid designers towards to design of laser sintering parts [129]. However, Ponche et al. proposed a new global approach to obtain appropriate design for AM processes, which starts directly from both functional specifications and AM process characteristics at the early design stage without an initial CAD model [130].

Klahn et al. provided two design strategies to use AM's benefits, which are a manufacturing driven design strategy and a functional drive design strategy [131]. A manufacturing driven design strategy enables a substitution of manufacturing processes at a later stage of the product life cycle, while a function driven design strategy increases the performance of a product. Reddy K. et al. used topology optimization along with DfAM rules to study the tradeoffs between the weight of the part, support requirements, manufacturing costs, and performance [132].

Yang and Zhao summarized there are two categories of DfAM research, which are the structure optimization design method and DfAM methodologies [81]. They concluded that DfAM research rarely considered manufacturability improvement. Most research focuses on optimizing the existing model designed by conventional design methods. Recently, Kim et al. presents a DfAM knowledge base containing a wide range of information including design features, manufacturing features and parameters which is formalized by web ontology and language [133]. This DfAM ontology facilitates the analyze of manufacturability of design features according to AM processes. However, more studies should be done considering manufacturability improvement for AM.

In addition, with the rapid development of information, computer and internet technologies, smart design and manufacturing systems is emerging with production integration with utilization of Internet of Things, clouding computing, big data, mobile internet and cyber-physical systems [134,135]. Zheng et al. discussed the conceptual framework, scenarios, and future perspectives for smart manufacturing systems [136]. Their proposed conceptual framework covers many relevant topics including design, manufacturing, monitoring, control and scheduling. Studies have been done to investigate the usage of different technologies in smart design and manufacturing, Wang et al. presents a comprehensive survey of commonly used deep learning algorithms and their applications in smart manufacturing [137]. From this survey, computational methods based on deep learning has potential to improve system performance and provide new visibility to decision-makers into their operation. Urbina Coronado et. al developed and implemented a manufacturing execution system with to track consumable usage, operator activity and production output powered by Android devices and cloud computing tools [138]. Tao et al. proposed a new data-driven framework to integrate product design, manufacturing and services in order to make the process more efficient, smart and sustainable [139]. However, these recent studies still did not consider the cognitive differences and communication problems between designer and manufacturers who are evolved in the product development process.

2.6 Expertise Level of Designers

This dissertation research focuses on novice engineering designers. Therefore, literature review is done on defining the expertise level of designers. Expertise is primarily a result of experience and a deliberate effort to improve [49,50]. To reach the stage of expert, it is largely agreed that certain amount of time and effort are required [4]. A minimum ten years (approximately 10,000 hours) of continued effort is a commonly accepted rule for an individual to become an expert, despite that time varies between individuals [49,50,140]. The primary mechanism to create expert-level performance in a domain is deliberate practice [49]. According to Ericsson and Charness, individuals cannot improve their performance and reach an expert level through automatic consequence of more experience with an activity, but through deliberate practice [141]. Deliberate practice is an effortful activity motivated by the goal of improving performance. It should be done by engaging in special exercises designed to improve performance in the skill with close guidance and timely, accurate feedback on performance. According to Gelder, the skills in a specific domain cannot be learnt from studying other subjects, it must be studied and practiced in its own way [142].

Several models have been developed to explain the levels of expertise and how they are reached. Laxton developed a three-stage model of design learning based on a metaphor of a hydro-electric plant [3]. First, the individual needs to accumulate expertise experience and knowledge (reservoir). Upon having the reservoir filled, the individual needs to establish the ability to generate ideas (generator) from the reservoir of knowledge. Third, the individual needs to develop the skills to evaluate and discriminate the ideas and interpret (transformer) them in new contexts.

Reimann describes a three-stage model of expertise development [2]. The novice state is characterized by knowledge representations. Problem solving is slow, search-based and error-prone at this stage. In the second stage, the knowledge structures are re-organized and adapted to specific tasks and constraints with growing experience. Problem solving is not so much based on searches and starts to become more automatic. In the last stage, an expert's knowledge has been developed by experience from specific cases. Problem solving is based almost exclusively in experience.

Patel and Groen identifies four different levels within the development of expertise, which are novice, intermediate, sub-expert and expert [143]. The knowledge of a novice is organized within causal and proportional networks. At the intermediate stage, these structures are compiled into a simplified network. The expertise of sub-experts is characterized by developing domain-specific scripts. As an expert, these structures become completely case-based scripts.

Dreyfus and Dreyfus describe a five-stage model of skill acquisition of expertise: novice, advanced novice, competence, proficiency and expertise [22]. A novice follows context-free rules created by designers with more expertise. An advanced novice uses rules and begins to note and cope with real situations. To achieve competence, the individual learns to devise a plan and choose a perspective. To achieve proficiency, the individual begins to see what needs to be done to solve problems intuitively instead of using reasoned responses, however, still uses reasoned responses to decide how to solve the problem. The expert decides both what needs to be done and how to do it intuitively. An expert can make more subtle and refined discriminations than the proficient performer.

Based on this five-stage model, Lawson describes the steps to achieve them [52]. First, an individual must develop a set of schemata. Then, a designer can begin to acquire experiential and episodic knowledge from precedents. When some experience has been gained, the designer begins to develop guidance principles to assist him/her to direct knowledge. Then, the designer starts to develop the skills to recognize the features of problems. Finally, the expert develops “rules of thumb” to simplify problems and solutions.

Also based on the Dreyfus model, Lawson and Dorst describe a seven-stage model by adding two more stages [144]. Beyond expert, a master performer develops an increased recognition of context and perception of subtle clues in design problems. Finally, a visionary can create new methods of performing design.

Three stages of expertise levels are usually investigated in studies: novices, advanced novices and experts. Novices are usually in the early stage of their training in one domain. Experts are people with a minimum ten years of experience. Advanced novices are somewhere between the novices and the experts, and are also called "expert-like novice", "novice experts", or "informed designers" [1,22,145].

The novices are individuals with little domain knowledge, experience and formal training. In this study, novices do not only include students but also include practitioners with certain characteristics. The characteristics of novice designers are summarized by several studies. Novices are inexperienced in design and are at the phase to accumulate expertise knowledge and experience [3]. When approaching design problems, novices often do it deductively and reason backward [12]. Novice designers tend to consider a single solution before considering alternative solutions when solving problems [146]. In addition, novices use trial-and-error in design due to their limited experience and evaluation ability [4,12,14]. At the beginning of the design process, novices usually focus on the surface-level features of a design problem [4–7]. They tend to oversimplify problems and start their work by providing solutions almost immediately [147]. Novices ignore constraints [20], and produce ideas that emphasize superficial aspects of potential solutions [1]. Therefore, their problem solving process is slow and error-prone [2]. Novices designers prefer to follow rules that are decomposed into context-free features by experts [22]. However, they may apply rules without evaluating the applicability to the design problem critically [24]. In addition, novices focus on defining the problem and spend a lot of design time on it [21]. During the design process, novices tend not to do reframing [144]. Their limited experience and capability make them unable to evaluate designs before testing them [4,12,14].

Advanced novices possess some experience and formal training in design [1]. Comparing advanced novices and novices, advanced novices are able to gain more information than novices and transition more frequently between different types of design activities [4,21,148]. They can also better prioritize gathered information [149]. Novices treat design problems as well-defined, end-of-chapter textbook problems [150,151]. However, advanced novices see design tasks as “ill-structured” [152]. Advanced novices consider more alternative solutions during the design process [149]. However, advanced novices are more prone to become fixated on a specific design solution [6]. Advanced novices also consider more criteria during the design process and may take a longer time to solve problems than novices [21]. When working on drawings, advanced novices prefer to use symbolic references. However, novices prefer to use formal geometric descriptions [144,153].

The characteristics of experts are also explored by a number of studies. Experts are open-ended, spontaneous, flexible and open to new experiences [144]. They are exposed to a great amount of example problems and solutions and have a significant amount of domain knowledge. Experts have the ability to recognize underlying principles easily when solving a design problem [4–7,51]. They tend to use a systematic approach when solving design problems [4,154], and they tend to use case-based reasoning [155].

Experts are capable of recognizing situations related to the specific problem [144,153]. In addition, experts can make preliminary evaluations of design plans before implementing and testing them [4,7,12,14,144]. When examining products, experts tend to see them in general as designs instead of just completed objects. Expert designers have eight basic core features of design ability [156]:

1. Produce novel and unexpected solutions
2. Tolerate uncertainty, working with incomplete information
3. Apply imagination and constructive forethought to practical problems
4. Use drawings and other modeling media as means of problem solving
5. Resolve ill-defined problems
6. Adopt solution-focusing strategies,
7. Employ abductive, productive and appositional thinking
8. Use non-verbal, graphic and spatial modeling media.

By comparing experts and novices, experts seem to require more information when approaching design problems [157]. They also gather more information during the design process than novices [157,158]. When making design decisions, experts aim to understand the challenge [151], and avoid making any early design decisions [1]. However, novices, tend to make design decisions prematurely [1]. When approaching design problems, novices often reason backward; however, experts tend to reason forwards and sometimes alternate between forward and backward reasoning when approaching more complex problems [12]. Novices tend to solve design problems in a linear order [1]; however, experts tend to solve problems in an iterative process [144,148], and they tend to seek out more sources of inspiration and information [155].

Novices are more reluctant to ask for recommendations and help than experts [12]. However, experts are more likely to become fixated on a single design [159]. For the cognitive differences between novices and experts, experts operate at a faster speed and more efficiently [4,11]. Experts also have better spatial memory and organizational structure [12,13,160,161]. When doing sketching, experts show more cognitive activity than novices [14]. By comparing advanced novices and experts, advanced novices' pattern-matching skills tend to be less reliable, and their ability in retrieving and using learned ideas is less flexible [1].

In this literature review, the characteristics of novices, advanced novices and experts are summarized. Novices tend to follow rules developed by experts. However, no studies have been done to evaluate the expertise level of individuals in the specific area of DFM. Therefore, this knowledge gap should be filled by studying the differences of DFM novices and experts, and how to accommodate these differences to assist them to communicate in a more effective and efficient way. The expertise model for designers could be adjusted to explain the expertise level in DFM. In this research, DFM novices are in the stage of accumulating DFM expertise experience and knowledge. The DFM experts have developed skills to evaluate ideas and interpret them in new contexts.

2.7 Summary

This literature review presents an overview of environmental impacts, fabrication failures, current DFM guidelines, automated feedback strategies for both AM and SM, communication between designers and manufacturers and the expertise level of designers. From this literature review, it is evident that there are knowledge gaps existing, and studies should be done to fill these gaps.

Fabrication failures could have significant impacts of the total building costs and environmental impacts. However, only a few studies focus on fabrication failures. The environmental impact influenced by fabrication failures is an important aspect to explore. Then, DFM guidelines should be used to decrease the environmental impacts and fabrication failures of CAM processes. DFM guidelines are well developed for conventional manufacturing. However, design for AM guidelines are still in development. Manufacturers can assist novice designers to apply DFM guidelines. However, differences in interpretation can result in mistakes or miscommunication in the design or processing stages of development. Therefore, software systems should be developed to assist the decision-making process. An overview of existing automated DFM approaches and methods is presented. Finally, this research focuses on novice engineering designers. Existing literature discussed designer's expertise level in detail. However, few studies have been done to evaluate the expertise differences of DFM novices and experts, and how to accommodate these differences to assist them to communicate in a more effective and efficient way. In conclusion, an automated DFM software tool should be developed for novice designers to reduce burden on human experts and provide feedback effectively in order to decrease the fabrication failures.

CHAPTER 3. ENVIRONMENTAL IMPACTS OF FABRICATION FAILURES OF FDM

3.1 Overview

Fused deposition modeling (FDM) is one of the most widespread AM techniques [162], particularly in university makerspaces. Barrett et al. found that desktop FDM machines, such as MakerBots, are the most common piece of equipment by studying 40 makerspaces that were identified from 127 top undergraduate institutions in the United States [163]. In FDM, a part is produced by extruding molten material to form layers as the material hardens. Desktop-grade FDM printers are popular because of their compact sizes, affordable prices (<$5000), and low maintenance costs.

Many desktop FDM printers are used in novice environments, and a knowledge gap exists regarding workflow and environmental impacts under these conditions. The desktop FDM printers are comparably easy to operate; free open-source slicer software tools, such as Cura and Slic3r, make it so that a user may simply upload STL files and hit print. As a result, FDM printers are expected to make AM a tool for everyday household life with high scrap rates [164]. Because the users of such printers are often inexperienced in operation and design methodologies for 3D printing, the actual environmental impacts could be larger than that under controlled experiments without human or printer errors.

Failure could increase both the material and energy consumption, which undermines the environmental benefits of FDM. Failed prints might be produced for various reasons, such as insufficient preheating time, inappropriate geometry of parts or printer malfunctions. When evaluating the material waste from FDM, most studies only consider the support material generation, in other words, the production under ideal conditions without failures. To address this gap, this study reports results of a printing failure study in two open shops with daily users of various levels of expertise.

Estimating the energy impact, however, is difficult, as a variety of FDM brands and machines exist with little data on their performance, resulting in high uncertainty. Kellens et al. summarized the currently available data on the average energy intensity of a variety of AM processes, and report a range of 83 MJ/kg to 1247 MJ/kg for commercial FDM machines [165]. This wide range describes professional machines and controlled testing; wider ranges might be found in uncontrolled environments for desktop grade machines. Therefore, there is a need for more data on the variability of manufacturing processes in general.

As such, this study provides a first estimate of parameter and scenario uncertainties in estimating desktop FDM machine energy and material consumption. The handling of variability and uncertainty is a common challenge in conducting a life cycle assessment (LCA) [166–168], and often requires both qualitative [169] and quantitative [170] methods to assess. Life Cycle Inventory (LCI) databases often lack variability information, which produces great uncertainty in the results of LCAs employing them. For example, even though the EcoInvent database allows probability distribution metrics, often they are unavailable and subjective default values are used instead [171].

Uncertainty is categorized into three types: (1) scenario uncertainty, (2) model uncertainty, and (3) parameter uncertainty [172].

1) Scenario uncertainty refers to the considered event and selection of data sources. Early attempts to incorporate an assessment of scenario uncertainty promoted a qualitative rating on the data source [169,173].

2) Model uncertainty arises from the researcher's structure of variable relationships or selection of mathematical models [174–176]. Analytical differential error propagation may be used to account for the error within a given model, but not across differing models.

3) Parameter uncertainty describes the random variation associated with individual variables in a model. Stemming from the early work on scenario uncertainty, parameter uncertainty has received a significant amount of attention through statistical measurement and simulation [177]. A common method for life cycle inventories (LCIs) and LCAs that include a variability or uncertainty component is a Monte Carlo simulation [178–180].

This study provides data and evidence for addressing scenario and parameter uncertainty in energy and material balances for FDM printers in user facilities. Parameter uncertainty is addressed directly through primary data collection and statistical descriptors; scenario uncertainty is included through duplication at multiple sites and machines. This study was conducted in two user facilities where a broad range of users with varying experience and expertise have access. These two open shops are representative of the numerous maker spaces and shops appearing in businesses, homes, colleges, communities, and schools around the world [163]. The results of each scenario are useful individually and collectively. Model uncertainty is not directly addressed in this work.

3.2 Methodology

This study focuses on desktop grade FDM printers using plastic in maker and engineering spaces. The framework and consideration of scrap production is more broadly relevant to many future applications of high embodied energy materials, as might be used in FDM manufactured cars or buildings. The functional unit is 1 kg of final product, and the energy and scrap production are examined. Operating factors such as machine utilization, material type (PLA/ABS), and specific machine are also considered. The theoretical framework is discussed first. Then, the material waste collection and energy consumption data collection at both sites are described. Finally, the data integration and comparison of these two sites are discussed.

3.2.1 Theoretical Framework

Two scenarios were considered and the parameters for energy and material variability were calculated from sample data. Scenario A is an open makerspace located at Georgia Institute of Technology (Site 1: GT), and scenario B is a user-limited makerspace located at University of California (Site 2: UC) at Berkeley. For both scenarios, two types of raw material were observed: ABS and PLA. In scenario A (GT), three different types of printers were tracked: Afinia H480, UP! mini, and UP! Mini 2. In scenario B (UC), only Type A Series 1 Pro printers were tracked. The material flow diagram of both sites is shown in Figure 3.

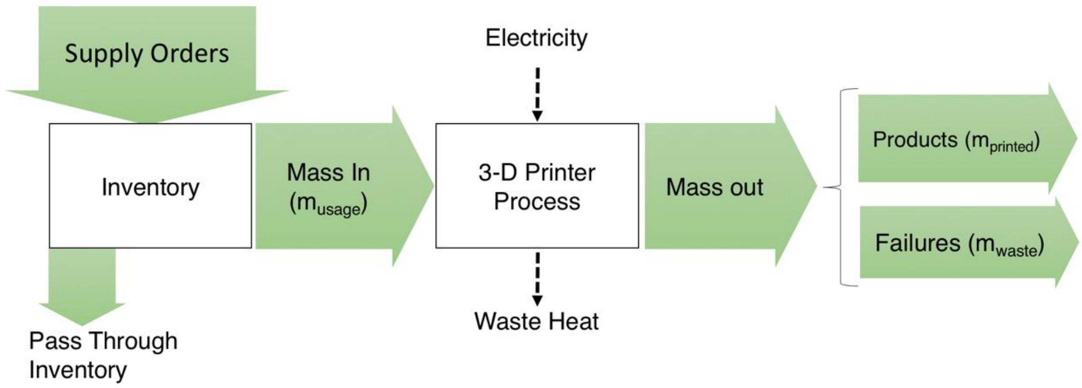


Figure 3 - Material Flow Diagram

Uncertainty in the study is reported by comparison across different scenarios and variance in the parameters of those scenarios using a single consistent model. A regression of the collected data provides coefficients for the scenarios considered, indicating predictive parameters, as in Equation 2,

$$Y = b_0 + b_1X_1 + b_2X_2 + \cdots + b_nX_n \tag{2}$$

where Y is the dependent variable, b_i's are coefficients, and X_i's are independent variables. The variance in data collected within and across sites provides an estimate of the parameter uncertainty. Mass and energy measurement uncertainty is calculated using measurement device accuracy and standard statistical methods. The mass measurement devices and data loggers could introduce error into measured data due to the sensor and other electronics performance, such as the analog-digital converter. The accuracy of the mass balances used are 2 g. The measurement accuracies of the power data loggers range from 0.5% to 1.13%. Several parameters are defined for Equations 3 - 9 of this study. Each m denotes the mass [grams] of material collected per collection period. Each P denotes a power demand [Watts], t denotes time [seconds], R denotes a mass rate [g/day], EI denotes energy intensity in MJ/kg, and r denotes a key performance ratio. The specific variables are wasted mass, m_{waste}, initial filament inventory, $m_{inv_{\mathrm{i}}}$, ending filament inventory, m_{inv_f}, ordered filament, m_{order}, used filament, m_{usage}, and mass removed from makerspace, $m_{printed}$, rate of material waste, R_{waste} , rate of material usage, R_{usage} , scrap ratio per collection period, r_{scrap}, overall average scrap ratio, $r_{avgcrap}$, length of collection period in days, d_{sample}, days in each inventory check period, d_{supply}, printing energy intensity, EI_{print}, overall use energy intensity, EI_{use}, average printing power, P_{print}, average idle power, P_{idle} , average preheating power, $P_{preheat}$, printing time, t_{print}, preheating time, $t_{preheat}$, and average idle time per print, t_{idle}.

$$R_{waste} = \frac{m_{waste}}{d_{sample}} \tag{3}$$

$$R_{usage} = \frac{m_{usage}}{d_{supply}} = \frac{m_{inv_i}{+}m_{order} - m_{m_{inv_f}}}{d_{supply}} \tag{4}$$

$$r_{scrap} = \frac{R_{waste}}{R_{usage}} \tag{5}$$

$$m_{printed} = m_{usage} - m_{waste} \tag{6}$$

$$r_{avgscrap} = \frac{\sum m_{waste}}{\sum m_{usage}} \tag{7}$$

$$EI_{print} = \frac{P_{print} \times t_{print}}{m_{printed}} \tag{8}$$

$$EI_{use} = \frac{P_{print} \times t_{print} + P_{idle} \times t_{idle} + P_{preheat} \times t_{preheat}}{m_{printed}} \tag{9}$$

Structured linear regressions were computed separately for the waste rate and energy intensity as dependent variables using Equation 2. For the waste rate, the independent variables were material usage rate R_{usage}, site, and material type. Material usage rate was included to identify whether waste was dependent on material throughput. The mass of successful parts $m_{printed}$ is assumed to be the mass that leaves the facility and is calculated as the difference between m_{usage} and m_{waste}. It is assumed that an insignificant quantity of waste was disposed of elsewhere. Since the waste collection bins were clearly labeled and next to the printers, it seems unlikely users would take failed prints or support material out of the room. For the energy intensity, the independent variables were machine type, material type, and site. The offset, b_0, represents the baseline waste generation rate (or energy intensity) for the reference parameter set. Regressions and Monte Carlo simulations are normalized by the number of printers at the respective sites; waste is aggregated by site.

3.2.2 Material Waste Data Collection

Failed print and support material bins were provided at each site. Bin contents were collected and recorded periodically. Although the collection bins were labeled, some users incorrectly deposited material. Therefore, all the collected waste was evaluated manually for any sorting error. Specifically, failed prints that were discovered in the support bin were re-sorted into the failed bin, and vice versa.

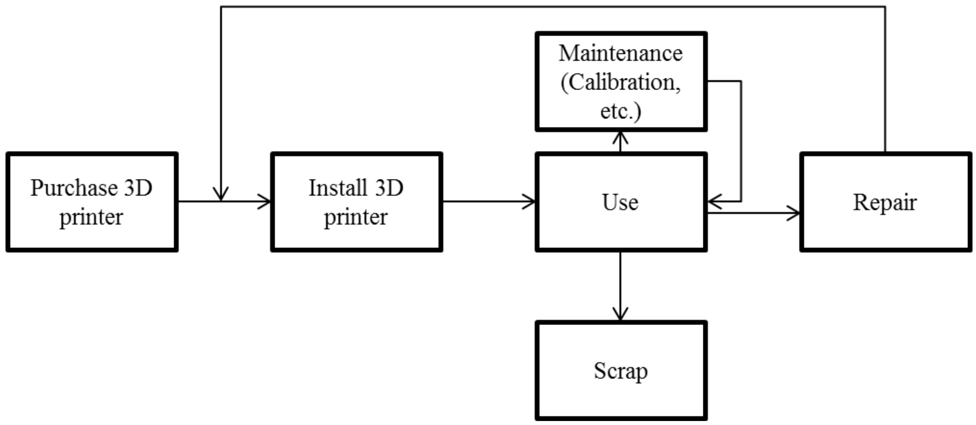


Figure 4 - Global Level 3D-Printer Activities

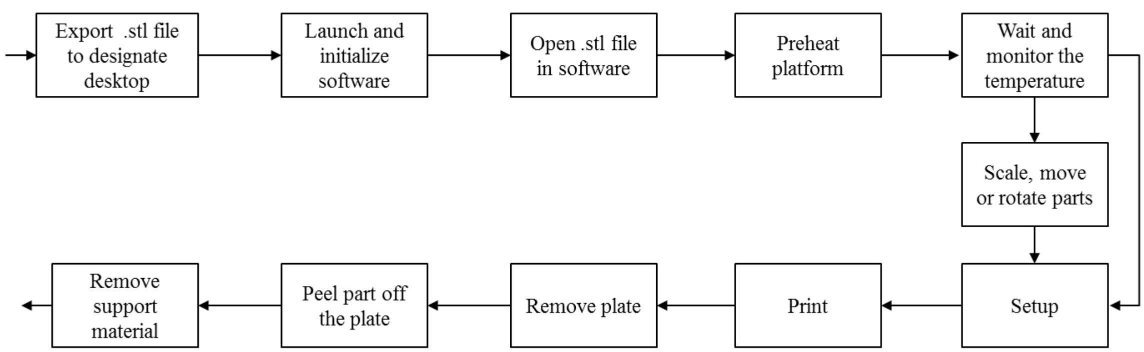
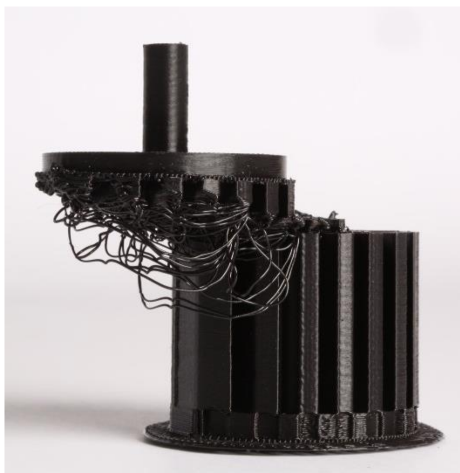


Figure 5 - Task Level 3D-Printer Activities

After each sample was collected and weighed, the parts were sorted by failure type to determine if failures were caused by human or machine error. Failure types were derived from available FDM printer troubleshooting guides [76–78], staff expertise, and activities of printer use. Activity diagrams [181,182] aided in determining which failure types had human intervention. The global level activity diagram, shown in Figure 4, involves aspects of the printer's useful life such as purchase, installation, maintenance and end-of-life activities. It is independent of single printing jobs. The task level activity diagram, shown in Figure 5, sequences the activities involved in the unit use of a printer. In total, 9 types of failed prints were identified. The example images and descriptions for each type of failure are shown in Table 1. These nine types of failure can be caused by user (machine operator) error, machine error, designer error, or any combination of these three types of error. Table 2 summarizes the causes for each failure type.

Table 1 - Example Images and Descriptions of Each Type of Failure

Type	Images	Descriptions
Unused Filament		Unused filament could be disposed if part of it distorts or tangles due to printer or user errors. An example is nozzle clogging. Also, if there is not enough material for the next print, the remaining filament could be discarded to ensure seamless operation.
Platform Heating	 	If the platform is not preheated or the temperature is not high enough, warping or cracking could happen. If the first layer of heated plastic cools down too fast, it may contract. Then, the edges of the print will bend upward until it no longer adheres to the print platform. Cracks in tall objects may also happen due to platform heating problems. The material cools down faster in higher layers than in lower layers, because the heat from the heated bed cannot reach that high. Therefore, adhesion in the upper layers is worse.

Type	Images	Descriptions
Part Shape		The prints may fail if the specification of the printer cannot support the part shape.
Layer Shift		Layer shift is caused by mechanical malfunctions with the printer; the extruder head does not move smoothly on the x- or y-axis, or the rods are not aligned correctly.
Support Material Removing Process		After the printer finishes a job, parts may be damaged during manual removal of the support material. Some of the support material may be difficult to remove because of the shape of the part.

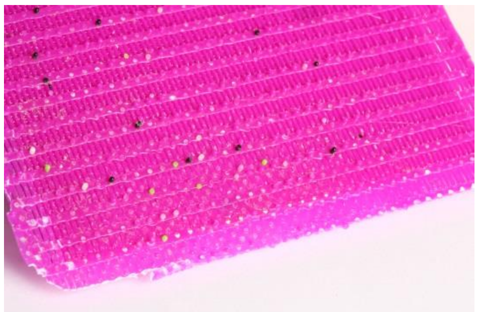
Type	Images	Descriptions
Printer Stops		Printer may stop automatically when it or an operator detects any error. Also, the printer may run out of raw material.
Tight Calibration		The nozzle and printing platform are calibrated too closely to each other. Therefore, the nozzle cannot extrude material properly. The first several layers may be compressed.
Loose Calibration		The nozzle and printing platform are calibrated too far from each other. Therefore, the first layer cannot adhere to the platform, and the sequential layers cannot adhere to each other properly.
Skip Layers		There are gaps in the model because some layers have been skipped in part or completely due to a printer error. The printer fails to provide the amount of plastic required for printing the skipped layers. There may have been a problem with the filament (e.g. the diameter varies), the filament spool, the feeder wheel or a clogged nozzle.
Non-physical defect	The part has no physical defect, which means it was not disposed because of printing errors but design or other issues.	

Table 2 - Causes for Failure Types

Type	User Error	Machine Error	Designer Error
Unused Filament	X	X	
Platform Heating	X	X	
Part Shape	X		X
Layer Shift		X	X
Support Material Removing	X		X
Printer Stops	X	X	X
Calibration	X	X	
Skip Layers		X	
Non-Physical Defect			X

Each sample was weighed separately on a scale, accurate to 2 g. All scales were calibrated using M2 class weights before and periodically throughout data collection. In the event multiple failure categories were represented in one sample, the failure that occurred first during printing was used for categorization. For example, if the part warped off of the bed and caused the upper layers to become entangled or malformed, the sample was categorized as a "platform heating" failure.

Material inventory was tracked periodically by counting the rolls of unopened filament and order quantities at each site. The mass of each new filament roll was recorded per supplier specifications and tolerances as .500, .750, or 1.000 kg. Rolls of material installed on machines were not removed for measure. The filament remaining on installed rolls was estimated at 25%, 50%, 75% or 100% of a new roll. The difference in remaining material was measured using a ruler from the outer edge of the roll for comparison with a new roll.

Filament diameter for all machines is 1.75 mm. All machines are capable of printing ABS and PLA.

Site 1: Georgia Institute of Technology (GT) Material Data Collection

Two labeled collecting bins were placed next to post-processing tables in the Invention Studio at Georgia Tech. This 3D printing room contained 12 Afinia H480 printers and 25 PP3DP UP! mini Generation 1 printers in which ABS filament was used. Approximately 25 printers were running at any time. For PLA filament, there were 10 Afinia H480 printers and 14 PP3DP UP! mini Generation 1 printers and 7 PP3DP UP! mini Generation 2 printers. Around 16 printers were running at any time.

The build volume of the Afinia printers is 140 x 140 x 135 mm. The vertical resolution is 0.15-0.40 mm. The build volumes of UP! mini 1 and UP! mini 2 are both 120 x 120 x 120 mm, with a vertical resolution of 0.20-0.35 mm. Extrusion rates for these printers are estimated to be 20-50 mm/sec.

Site 2: University of California (UC) Material Data Collection

A labeled cardboard waste bin was placed among the 9 Type A Series 1 Pro printers in the Jacobs Institute for Design Innovation makerspace. The build volume of each is 305 x 305 x 305 mm. The recommended vertical resolution is 0.05-0.30 mm. The feed-rate is 15-120 mm/s while extruding, 30-250 mm/s while traveling. These printers only use PLA during normal operation. This bin collected all unwanted and failed prints, as well as residual filament and support material. The contents of bin were collected periodically and sorted into 10 categories: the 9 failure modes and 1 final category for residual support material.

3.2.3 Energy Consumption Data Collection

Energy consumption data were collected at two sites on four different printers using 2 different machines. Power monitoring tests were conducted at both sites to establish equivalent comparisons between ABS and PLA, and among 4 different printers. These comparison tests specified printing a cup-shape design in three different orientations as test sets in both materials on each machine. For each test set, the printer preheated the printing platform for the required time. Then the printer started to print the cup-shape part in one orientation. Once the part was finished, it was removed from the platform. After the platform was cooled down to room temperature, printing of the cup-shape part in another orientation started, following the same procedure. Default material settings (heating levels) were used per manufacturer recommendations. Power monitoring equipment with sampling rate ranges from 0.1 Hz to 10 Hz were installed on each printer when printing the cup-shape parts. These parts were qualitatively examined for adequate and comparable quality. The mass of each printed part was also measured in order to calculate the printing energy intensities in MJ/kg.

In addition, the power consumption was tracked for the machines’ preheating, idle, and production time during daily production at the different sites. The idle time for each part is calculated by averaging all idle time between two separate printings during the entire monitoring time.

Site 1: Energy Data Collection

ABS Filament: To study the energy consumption of the Afinia H480 printer using ABS filament, an EXTECH 380803 Power Analyzer was connected to one printer to collect and record the power data. The power analyzer recorded the current power in Watts every 10 seconds (0.1 Hz). The sampling rate is relatively low, since the power analyzer can only store 1012 sets of data. Power data could be viewed from the software at 1 Hz, but not be stored. The energy consumption shown in the software was manually monitored, recorded, and compared to the 0.1 Hz data. The differences were negligible. One test set was done for the Afinia H480 printer using ABS filament. Additional long-term power data for daily production was monitored using the EXTECH with sampling rate of 0.007 Hz.

PLA Filament: To study the energy consumption of the FDM printers when using PLA filament, HOBO UX120-018 Plug Load Data Loggers were connected to 3 different printers in the open shop, which were the Afinia H480, UP! Mini 1 and UP! Mini 2. The power analyzer recorded the power in Watts at a sampling rate of 1 Hz. Three controlled test sets were recorded. The daily production using PLA filament was monitored using HOBO with sampling rate of 0.1 Hz.

Site 2: Energy Data Collection

Site 2 used a single Type A Series 1 Pro machine for test printing. A Yokogawa CW240 Energy monitor was connected to the printer to collect power and time data at a sample rate of 10 Hz. One test set was done using ABS filament, and one test set was done using PLA filament. The daily production was monitored using Yokogawa with a sampling rate of 10 Hz.

3.2.4 Site Consistency

The sites for data collection vary in population, access controls, machine type, primary material used, and researchers classifying waste. Site 1 is open access to all students and has more affordable machines running primarily ABS plastic. Site 2 is a paid access space (free material) with higher-end machines running exclusively PLA plastic. These differences suggest that site 1 might expect a higher waste production rate than site 2.

Equivalence tests between the two sites were conducted. First, machines at the respective sites swapped material types and printed the same design to provide equivalent power consumption rates. This test identifies machine specific power requirements, independent of material choice. Second, waste collected from each site was sent to the other and re-categorized in a blind test by researchers at each site. This inter-rater agreement test uses Cohen’s kappa to evaluate the level of agreement between site specific researchers.

3.3 Results and Discussion

This section will report the results from the material waste collection, energy consumption data collection, and the uncertainty and variability analysis, including regression and cross-validation.

3.3.1 Material Waste Results

Daily averages of waste for Site 1 were computed by weighting each collection total by the number of days since the previous collection and the number of machines in the facility. For ABS, a total of 36.6 kg of waste was collected for Site 1. The mean daily waste generation rate for an open shop was 402 g/day. For PLA, a total of 18.1 kg of waste was collected. The mean daily waste generation rate was 393 g/day. The summary of the waste in Site 1 is shown in Table 3.

From the data, the total material waste of PLA per day is less than the total waste of ABS. However, the mass of support material for PLA is larger than ABS; the mass of PLA failed parts is less than ABS. Based on the results, changing from ABS to PLA filament is likely to reduce the mass of failed prints. The glass transition temperature is 105 ℃ for ABS and 60 ℃ for PLA. The melting of PLA is 173 ℃. Therefore, PLA needs less pre-heating of the printing platform. PLA is also less like to warp, and calibration problems with PLA decreased compared to ABS. The failure caused by layer shift and printer stop increased, however, since the printers at Site 1 had exceeded their useful life expectancy. Around 67.6% of printers operated normally when using ABS in the first semester of study. However, only 51.6% of printers operated normally when using PLA in the later semesters. Therefore, the increased age of printers likely influenced the scrap ratio. Figure 6 shows the waste fraction by type of failure for Site 1.

Table 3 - Site 1 Waste Summary

Category	Weighted Daily Average PLA (g/day)	Total PLA Collected	Weighted Daily Average ABS (g/day)	Total ABS Collected (g)
Support Material	274	12605	181	16490
Platform heating	3	155	48	4330
Layer shift	26	1212	11	1028
Removal breakage	7	300	19	1684
Printer stops	38	1733	29	2668
Calibration	25	1144	76	6928
Skip layers	1	26	2	174
Filament	1	47	10	862
Deformed shape	14	643	20	1802
Non-physical	5	246	7	633
Cumulative	394	18111	403	36599

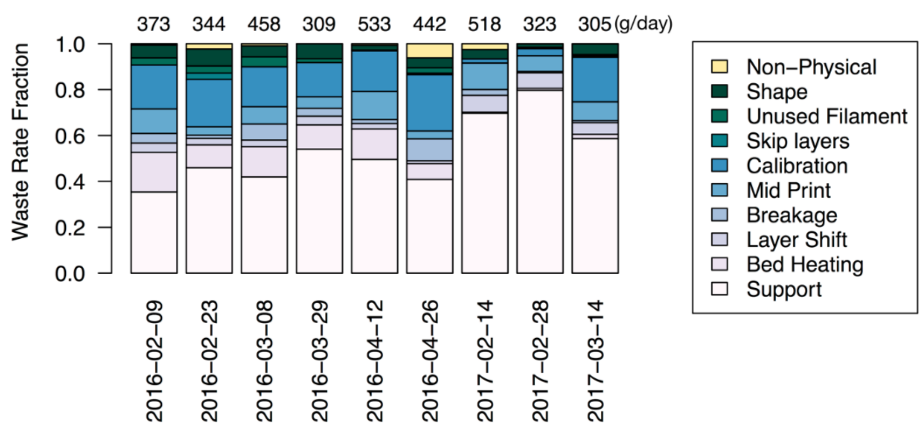


Figure 6 - Waste Fraction by Type of Failure for Site 1

For Site 2, waste generated in a student makerspace with paid access and free material was collected from both the fall and spring semesters in the 2016-2017 academic year. Collection occurred 8 times with varying duration between dates. Waste accumulated over the winter break was not included as it was generated solely by professional staff for research purposes. A total of 43.2 kg of waste was collected. The mean daily waste generation rate was 244 g/day. The summary of waste from Site 2 is shown in Table 4. Figure 7 shows the waste fraction by type of failure for Site 2.

Table 4 - Site 2 Waste Summary

Category	Weighted Daily Average (g/day)	Total PLA Collected
Support Material	87	15712
Platform heating	28	4834
Layer shift	30	5033
Removal breakage	10	1910
Printer stops	23	3978
Calibration	38	6780
Skip layers	9	1575
Filament	3	510
Deformed shape	13	2445
Non-physical	3	440
Cumulative	244	43217

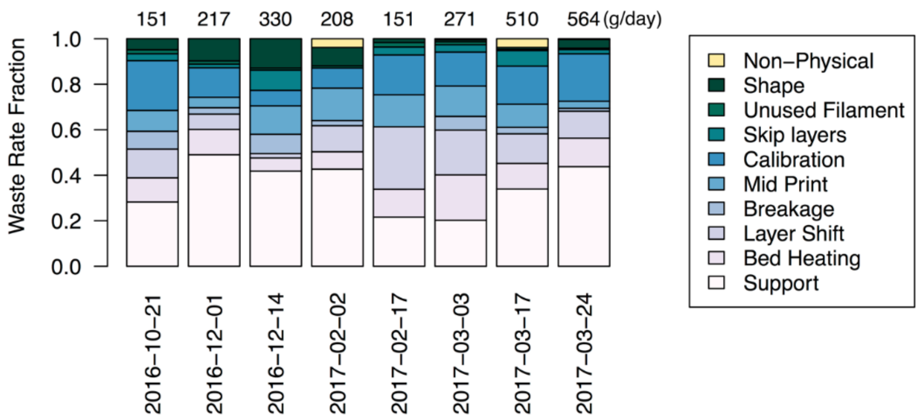


Figure 7 - Waste Fraction by Type of Failure for Site 2

It is assumed that the no significant quantity of waste was disposed of elsewhere, and the relatively high amount of waste supports this assumption. If the users wanted to study a failed part or had significant intellectual property concerns, they might take the failed parts out of the facility. Recording the variability week to week helps characterize the effects of such uncertainties.

3.3.1.1 Material Consumption Uncertainty and Variability

The waste rate (g/day) could be affected by site, material types, and material usage rate. Equation 10 shows the regression equation for waste rate, denoted by R_{waste}.

$$R_{waste} = b_0 + b_1 \times Site + b_2 \times Material + b_3 \times R_{usage} \qquad (10)$$

Table 5 shows the regression analysis results, which are based on Site 2 using PLA. The plot of the waste rate fit line is shown in Figure 8.

Table 5 - Material Waste Rate Regression Results

(g/day)	Estimate	STD Error	t value	P(>|t|)
Intercept (b_0)	246.3	44.55	5.529	9.73e-5(***)
SiteGT (b_1)	151.1	83.15	1.817	0.0923(.)
ABS (b_2)	23.85	86.72	0.275	0.7876
Material Usage Rate (b_3)	-0.00205	0.00387	-0.529	0.6055

*** means >=99.9 confidence; (.) means >=.9 confidence

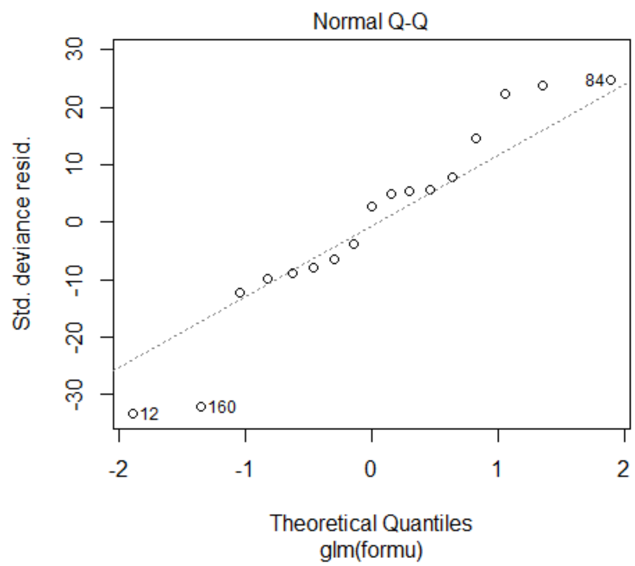


Figure 8 - Waste Rate Fit Line (Assumed Gaussian) and Data

The waste rate (g/day) regression indicates: ABS is associated with a higher scrap ratio; the base waste rate across sites was roughly 246 g/day; Site 1 had a higher waste generation rate; and material usage rate (proxy for production) is not a strong predictor of waste rates. This regression was weighted by the number of machines available at each site and the number of days between sample points.

The average scrap ratio for Site 1 using ABS is 0.35 and PLA is 0.40. The average scrap ratio for Site 2 using PLA is 0.23. Site 1 is an open space with lower barrier-to-entry machines (lower cost). Unlike Site 2, Site 1 does not require any training before using the printers. These differences could explain the higher rate of disposal, as the users may be more prone to errors and the machines more likely to cause an error. For Site 1, data were collected for a period during which only trained staff had access to the printers. The scrap ratio of this period is 0.26. It is similar to the average scrap ratio of Site 2. Therefore, the average scrap ratio of Site 2 might better represent printers used by trained users. The average scrap ratio of Site 1 can show the data for printers used by a mix of users. The baseline waste rate across both sites indicates what could amount to a significant addition to the municipal waste stream as more office users purchase machines.

Uncertainty in sorting among different sites was measured using Cohen's Kappa for an inter-rater agreement test. Waste collected from each site was sent to the other and re-categorized in a blind test by researchers at each site. Table 6 shows the interrater agreement measures and interpretation. Landis and Koch characterized values < 0 as indicating no agreement, 0–0.20 as slight, 0.21–0.40 as fair, 0.41–0.60 as moderate, 0.61–0.80 as substantial, and 0.81–1 as almost perfect agreement [183]. The Cohen's kappa ranges from 0.45-0.62, which is a moderate to substantial agreement between the two raters.

Table 6 - Summary of Cohen's Kappa

Output	Site 1	Site 2	Overall
Observed Agreement	0.68	0.55	0.63
Random Agreement	0.15	0.18	0.16
Cohen's kappa	0.62	0.45	0.55
Kappa Error	0.045	0.058	0.036
Interpretation	Substantial	Moderate	Moderate

3.3.2 Energy Consumption Results

Figure 9 shows the operation power at Site 1 and Site 2 using PLA.

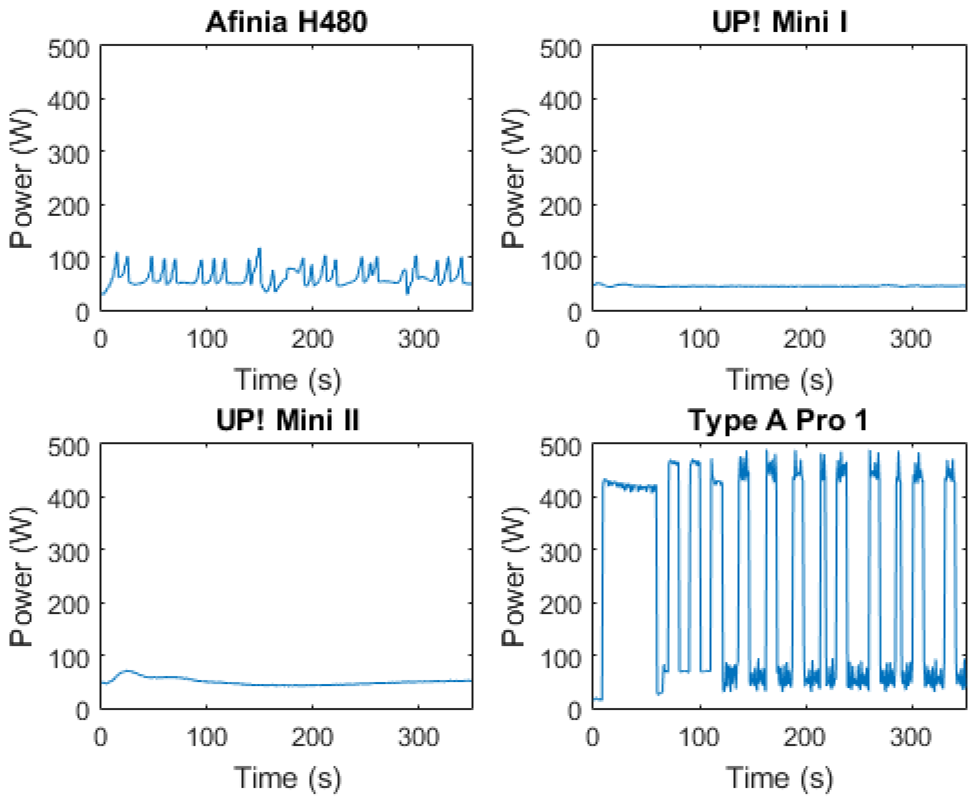


Figure 9 - Operation Power of Printers at Site 1 and Site 2 Using PLA

Table 7 shows the average of the preheat time and power for each stage. For Site 1, 53.7% of the time was in idle for the Afinia using ABS, 74.3% for the Afinia using PLA, 70.6% for the UP! Mini 1 using PLA, and 65.4% for the UP! Mini 2 using PLA. The makerspace at Site 1 opens 10 am to 6 pm for workdays. For 76.2% of the time, the makerspace is not open to public. However, the printers are not turned off after-hours. This could justify the relatively high idle time of the printers. Table 7 shows that the idle power is relatively high. Therefore, low operating time can increase the energy intensity significantly. 30.5% of the energy was consumed during the idle mode for Afinia using ABS, 37.5% for Afinia using PLA, 60.9% for UP! Mini 1 and 48.3% for UP! Mini 2. Hence, increasing the operating time of the printers can decrease the energy intensity and increase the efficiency of the printers. Moreover, the printers can be turned off when not in use to save energy. The makerspace at Site 2 was open 12 hours a day for workdays, and 6 hours on Saturdays, with an average idle time of 68%. Idle operation consumed 14.7% of the energy for ABS and 13.0% for PLA. The fraction of idle energy consumption at Site 2 was lower than Site 1 since the idle power is relatively small compared to the print and preheat power for TypeAPro1.

Table 7 - Energy Consumption Characterization Data

Printer	Material	Preheat time (s)	Preheat power (W)	Print power (W)	Idle Power (W)
Afinia H480	ABS	450	74.2	82.6	31
Afinia H480	PLA	98.5	100.8	52.7	30
UP! Mini 1	PLA	71.5	71.6	49.3	25
UP! Mini 2	PLA	55.4	90.8	49.2	24
TypeAPro1	ABS	487.6	245	245	19.9
TypeAPro1	PLA	110	299	299	21.1

The print power for PLA is less than that for ABS, likely due to lower platform and nozzle temperatures. In addition, the printers using PLA required shorter preheating time (usually less than 1.5 minutes) compared to the printers using ABS. Thus, the preheat energy consumption using PLA is less than that of ABS.

3.3.2.1 Energy Consumption Uncertainty and Variability

Equation 11 shows the regression equation for the energy intensity, EI. The unit of the energy intensity is MJ/kg.

$$EI = c_0 + c_1 \times Machine + c_2 \times Material + c_3 \times Site \tag{11}$$

The print energy intensity (MJ/kg) could be affected by machines and material types. Table 8 shows the regression analysis results, which is based on the Afinia H480 printers using ABS. The plot of the energy intensity fit line is shown in Figure 10.

Table 8 - Energy Intensity Regression Results

MJ/kg	Estimate	STD Error	t value	P(>|t|)
Intercept (c0)	26.27	2.682	9.797	2.09e-8(***)
UP1 (c1)	1.776	4.143	0.429	0.673
UP2 (c1)	3.715	3.973	0.935	0.363
TypeAPro (c1)	21.368	2.894	7.383	1.07e-6(***)
PLA (c2)	-18.147	2.847	-6.374	6.93e-6(***)

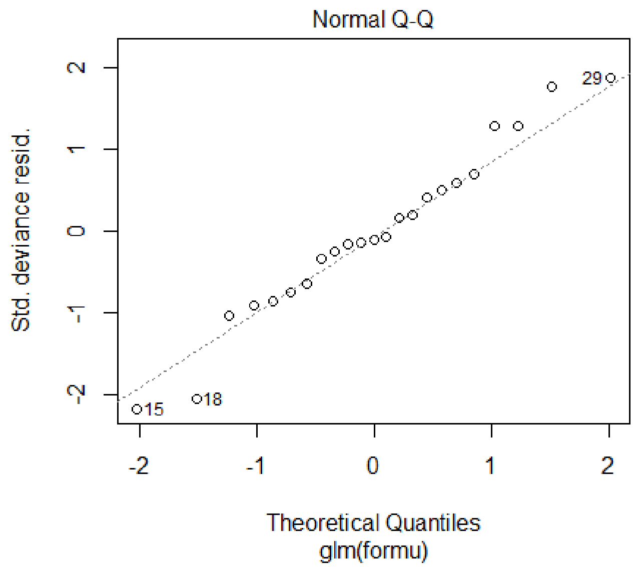


Figure 10 - Energy Intensity Fit Line (Assumed Gaussian) and Data

The energy intensity regression indicates that: PLA is less energy intensive than ABS; the Afinia is the least energy intensive machine to use for a given amount of material; the choice of material and machine may play a significant role in determining the energy intensity; and the TypeAPro is the most energy intensive machine. TypeAPro has larger building envelop than the Afinia, UP! Mini 1 and UP! Mini 2, which could explain the much larger energy intensity. This regression was weighted by the amount of time for each test in collecting the energy intensity quantities.

3.3.3 Monte Carlo Life Cycle Inventory Results

The data collected provide statistical parameters that can be used for Monte Carlo simulations of FDM LCIs. The life cycle of FDM includes four major stages, which are (1) the primary production including the polymerization and granulate formulation, (2) the filament making, (3) FDM including preheating and printing, and (4) end of life. Four different simulations of LCIs were done using 10,000 samples: (1) LCI without setting material type or location and assuming no failure, (2) LCI with failure variability but not defining material type or location, (3) the LCI of Site 1 using ABS filament considering failure, and (4) the LCI of Site 2 using PLA filament considering failure. For the LCIs that did not define the material type or location, the material types and location were considered equally probable. The Site 1 ABS and Site 2 PLA were selected as the two materials and location possibilities because these data are the most reliable, and Site 2 does not use ABS.

Table 9 - Statistical Parameters and Results for the Monte Carlo Simulation

Parameter	ABS		PLA		Site 1 ABS		Site 2 PLA	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Primary Production (MJ/kg)	95.20	N/A	51.70	N/A	95.20	N/A	51.70	N/A
Extrusion to filament (MJ/kg)	6.08	N/A	5.94	N/A	6.08	N/A	5.94	N/A
Centralized Recycling (MJ/kg)	9.99	N/A	17.55	N/A	9.99	N/A	17.55	N/A
Preheating (MJ/kg)	1.55	0.79	0.38	0.40	1.87	0.24	0.96	0.22
Printing (MJ/kg)	39.80	16.34	16.65	7.71	20.74	1.39	25.76	5.15
Idle (MJ/kg)	7.04	-	7.35	-	9.50	-	4.01	-
Avg Scrap Ratio (%)	27.15	18.66	29.58	4.02	29.58	4.02	14.76	6.01
Total Energy Intensity (MJ/kg)	-	-	-	-	204.29	12.07	125.01	10.79

For the overall LCI, it is assumed the PLA and ABS are equally likely to be used. Therefore, the energy data for the overall simulation are the average of the energy data for PLA and ABS. Table 9 shows the mean and standard deviation (STD) of the parameters used in the simulations. The probabilities were assumed to be normally distributed. The energy data for primary production, extrusion to filament and centralized recycling are from CES Edupack 2016 [184].

Figure 11 shows the frequency distribution of the Monte Carlo simulation results for the overall energy intensity with and without failure, and the frequency distribution of the overall energy intensity with failure, Site 2 PLA and Site 1 ABS results. The 95% confidence interval of the energy intensity for the overall energy intensity without failure is 112.39-147.38 MJ/kg, for the overall energy intensity with failure is 127.27-288.41 MJ/kg, for Site 1 using ABS is 182.50-229.89 MJ/kg, for Site 2 using PLA is 105.80-147.96 MJ/kg. Therefore, if printing failure is considered, the energy intensity range is 127.27-288.41 MJ/kg for 95% confidence without setting material type or location.

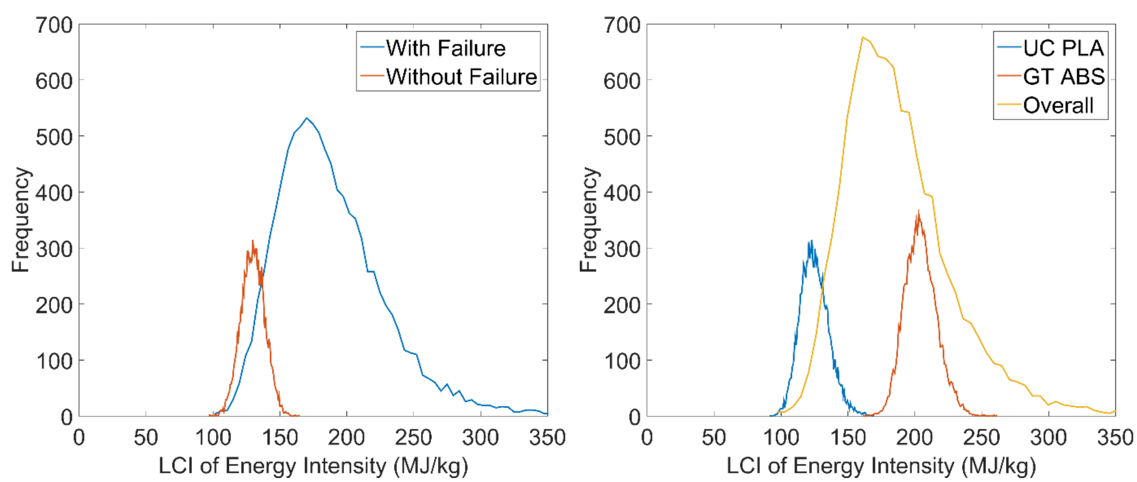


Figure 11 - Frequency Distribution of the Monte Carlo Simulation Results

Generally, the PLA material uses less energy than ABS. The printing failure could increase the energy usage by 45.1% for the mean value. From the large standard deviation of the overall LCI with failure results, the printing failure increases the uncertainty of the LCI significantly, from a standard deviation of about 9 to 40.

The assumption that the two sites provide equally likely representations of printing behavior requires more investigation. The two sites have different characteristics, and Site 1 ABS has a much larger scrap ratio than Site 2 PLA. Material differences, printer differences and operator differences are all possible causes – with operator difference being a likely distinguishing factor. Site 1 is an open shop with lower barrier-to-entry machines (lower cost). Student volunteers operate the facilities, rather than dedicated personnel. The machines at Site 1 experience heavier loads and are generally older than the Site 2. Although there were some limitations, the simulation results, especially the confidence intervals, show the range of LCI of energy intensity for the desktop-grade FDM.

3.3.4 Discussion of Broader Impacts

Regression analysis indicates that the rate of material usage is not a strong predictor of waste rates. The amount of waste generated across both sites indicates that more ubiquitous access to 3D printing may add considerably to the waste stream. If one machine similar to those in this study is provided for every 100 K-12 students, or 2-5 classrooms, in the United States (~55 million students), our data estimates roughly 110 TJ (30 GWh) of energy consumed and 160 MT (176 short tons) of waste generated per year alone.

3.4 Summary

This chapter quantifies the environmental impacts of desktop FDM printers in two different makerspaces. For the material consumption, the baseline waste rate across both sites average 35-45%, and may indicate a significant plastic waste increase as more personal and school users purchase machines. For the energy consumption, the energy intensity range is 127.27-288.41 MJ/kg for 95% confidence, if considering fabrication failures. If desktop FDM printer adoption nears that of inkjet and laser printers, FDM printers will consume large amounts of energy and material. For inkjet and laser printers, Kawamoto et al. (2002) estimated that the stock of laser printers was 28 million and the stock of inkjet printers was 74 million at the end of 1999, consuming 6.23 TWh/year and 2.88 TWh/year, respectively.

This chapter also reported the uncertainty and variability in energy and material consumption of desktop FDM. The material usage rate was not a strong predictor of waste rate. The TypeAPro was the most energy intensive machine among those studied. More failures were observed with ABS than PLA. Overall performance may change with application, however. Site 1 had a higher waste generation rate. Because Site 1 is an open space with lower barrier-to-entry machines, the users may be less vigilant. The machines were also more error prone. Categorization uncertainty was measured in a blind test re-categorization of inter-site waste by researchers at each site. The inter-rater agreement analysis of this blind test indicates the sorting instructions are reliable but may not be comprehensive.

Based on the observations, user experience level may influence scrap ratio and energy consumption. Cerdas et al. found that experienced users could better select printing parameters that minimized waste [185]. In addition, the part geometries and printing parameters could also influence the scrap ratio. As such, next, Chapter 4 examines the impacts of user experience level, part geometry and printing settings on fabrication failures in order to determine the causes for failures in desktop FDM.

This framework can be applied to a broader set of processes, machines, materials, and impact considerations, such as CNC machining. The investigation of environmental impacts of CNC machining within novice environments was not performed in this study. However, this framework could be applied to CNC machining with minor adjustments in the operating phases considered for energy consumption and failures modes. The failure sorting instructions should also be modified for the CNC machining process.

CHAPTER 4. CAUSES FOR FAILURES IN DESKTOP FDM

4.1 Overview

Chapter 3 showed that the environmental impacts of AM could increase dramatically due to inexperienced users and malfunctions of inexpensive machines. Novice users, the major users of desktop FDM printers, are often inexperienced in design and operation, and can make improper decisions leading to fabrication failures. In addition, the inexpensive desktop FDM printers are more prone to malfunctions, which can also result into fabrication failures.

Such failures may be useful in education because they can help students to better understand the structures and constraints of problems [15]. Embracing failure has also been identified as one of the three guiding principles for an educational makerspace [186]. However, youth can experience the failures of making as demoralizing [16]. In addition, since there are always a limited number of printers in a makerspace, failures can result in inefficiency of the makerspace operation.

Many of the printing failures could be caused by user behaviors. User behaviors could result into uncertainty and variability when estimating environmental impacts of FDM printers. For example, a makerspace that does not require any training before using the printers could lead to higher environmental impacts [17]. Investigating user behaviors to reduce environmental impacts of FDM printers is especially important because FDM is expected to make AM a tool for everyday household life [187]. According to Wohlers

Report [188], more than 278,000 desktop 3D printers were sold worldwide in 2015. The market of desktop 3D printers further grew by 49.4% worldwide in 2016 [189].

Few studies have investigated the causes of fabrication failures in makerspaces. User experience and expertise level may influence the possibility of fabrication failures. This chapter aims to investigate how failure rates change with user experience and expertise level in university makerspaces. The printing failures and daily users of various levels of experience were studied in an open-access university makerspace. Specifically, user experience level, computer-aided design (CAD) models, printing parameters and results were tracked and analyzed.

4.2 Methodology

For this research, one hypothesis was tested: failure rates decrease if users have more experience and higher education level. The type and number of FDM failures and user demographics in a free-access university makerspace (the Invention Studio at the Georgia Institute of Technology) were studied. The makerspace is run by trained volunteers who are undergraduate and graduate students. All students can use the printers without training requirements. This study was approved under protocol H17008 by Georgia Tech IRB.

The Invention Studio has a 3D printing makerspace with 9 Ultimaker 2+ printers in Fall 2017 semester, and 10 Ultimaker 2+ printers in Summer 2018 semester. The Ultimaker 2+ printer is a FDM printer with build volume of 223 x 223 x 305 mm and resolution of 0.02 to 0.60 mm. The printers used PLA as the raw material.

From our previous research in this makerspace [18], the failure rates were collected every two weeks in one semester and found that the failure rate for one time period was significantly lower than other time periods. That time period was spring break, during which the makerspace was closed to public and only trained staff could access it and use the printers. In addition, the makerspace that requires training before using the printers led to lower failure rates than the makerspace that does not require any training, based on prior observation. Therefore, it is hypothesized that user experience level may influence failure rates.

To test the hypothesis, the CAD files, failed parts and energy consumption within the makerspace were collected and analyzed. For each CAD file, the source of the part was recorded, if it was created by the user or downloaded from online websites such as GrabCAD.com and Thingiverse.com. Additionally, individual students using the printers and the decisions that they made were observed. Users' experience information including education level and number of times using CAD software and 3D printers was collected in order to test the relationship between failure rates and users' design experience level, operation experience level and education level. The following multiple-choice questions were used in the survey:

1. For how many projects have you used CAD software?

    a. <3

    b. 3-5

    c. 6-10

d. >10

2. How many different parts have you printed on a 3D printer?

    a. This is the first time

    b. <5

    c. 6-10

    d. More than 10

3. How often do you use 3D printers in the Invention Studio?

    a. <4 times/semester

    b. 1-3 times/month

    c. 1-3 times/week

    d. >3 times/week

4. Which year of study are you in?

    a. Freshman

    b. Sophomore

    c. Junior

    d. Senior

    e. Masters

f. MS/PhD

g. PhD

The printing parameters set in the slicer software were recorded, including layer height, infill density, print speed and support material settings. The slicer software used in the makerspace is Ultimaker Cura. The user interface of Ultimaker Cura is shown in Figure 12. In addition, the users were not allowed to alter the temperature of the extruder nor the printing bed.

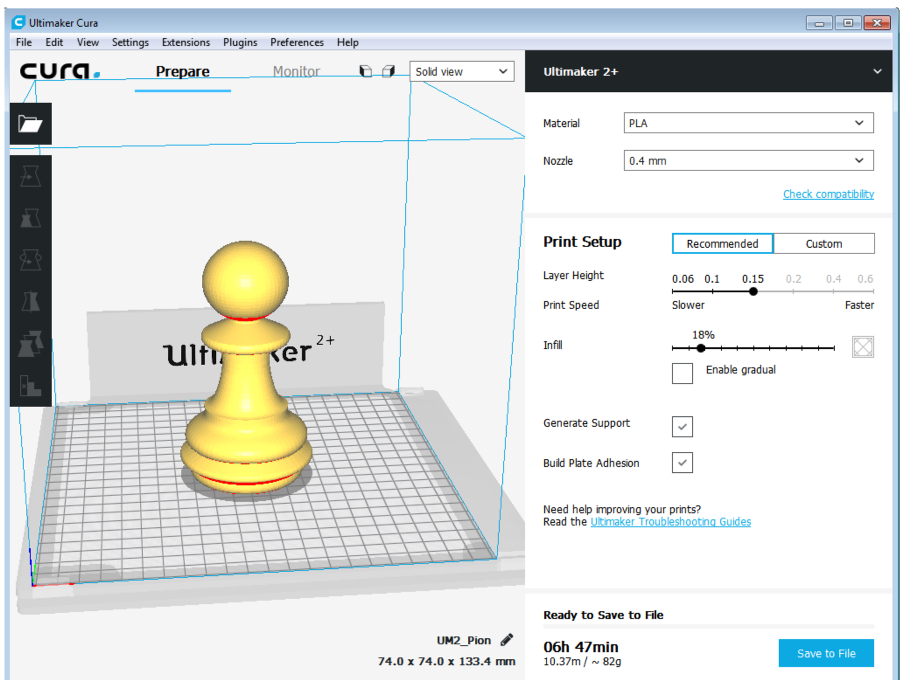


Figure 12 - User Interface of Ultimaker Cura

For each printing job, the printing result of a success or a failure was recorded. The users were asked if they considered the print a success or a failure and checked for physical defects. If the print failed, the failure cause was recorded.

To measure the energy consumed by failed prints, HOBO UX120-018 Plug Load Data Loggers were connected to 6 Ultimaker 2+ printers in the makerspace. The data logger recorded the power in Watts at a sampling rate of 0.1 Hz. The data from the loggers were exported and saved regularly. Based on the collected information, the energy consumption data for failed prints were extracted and recorded. The mass of the failed prints was measured using a scale, accurate to 2g.

The collected data were analyzed to show the causes of failures. Three sets of analysis of variance (ANOVA) were done for the user's experience level, the source of the part, and the printing settings.

4.3 Results

In total, 95 sets of individual observations were recorded with 39 failed prints. The overall failure rate was 41.1%. The average energy consumption per part was 3.0 MJ. The average mass of the failed parts was 28 g. The printing energy intensity is 107.1 MJ/kg. Table 10 summarizes the failure category, primary cause, detailed cause and number of failed prints with respect to each failure cause.

Table 10 - Failure Causes and Number of Prints

Category	Primary Cause	Detailed Cause	# of Prints	
Designer	Support Material	Support cannot be removed	2	9
	Feature Size	Complex features	3	
		Cannot assemble	2	
		Wrong part size	1	
		Wrong hole size	1	
Operator	Printing Settings	Did not generate support	2	16
		Printed out of area	1	
	Printer Operation	Loose calibration	8	
		Platform was moved	1	
		Printed wrong file	1	
		Out of filament	2	
		Filament tangled	1	
Machine	Machine Malfunction	Skip layers	1	14
		Nozzle clogged	10	
		Layer shift	3	

Among the 39 failures, nine failures were caused by designer errors. Two prints failed because the designers did not consider the support material removing process. Therefore, the support material could not be removed and ruined the surface finish. Since support material is not needed for traditional manufacturing processes, the novice designers may not consider it. Nine prints failed because of improper feature sizes. If the designers did not consider the resolutions of the FDM printers, they may design too complex and/or too small of features, which cannot be printed. If the designers did not consider the tolerances of the FDM printers, the mating parts could not be assembled. In addition, two parts failed because the designers specified wrong feature sizes for printing.

Sixteen failures were caused by operator errors, including improper printing settings and operations. Three prints failed because the operators did not choose to generate support material for parts with overhang structures. From the observations, the operators did not click the option to generate support material in the slicer software because they did not know what the function of support material was. One part failed because the operator placed the part outside of the printable area of the printer in the slicer software. Eight prints failed because the printers were not calibrated properly. Therefore, the prints could not adhere to the printing platform and warped; the layers of the prints could not adhere to each other either. One print failed because the printing platforms were moved accidentally during the printing process. One print failed because the operator uploaded or selected a wrong file to print. Three parts failed because the operators did not check the status of the filaments before printing. Among these three failures, two prints failed because the remaining filament was not enough for the parts. One print failed because the printer was not able to extrude the tangled filament.

Fourteen failures were caused by machine errors. The primary cause was nozzle clogging (71.4% of machine failures). Nozzle clogging could be caused by incorrect temperature for extruding, poor quality filament, tight calibration and printer aging. To decrease the environmental impacts of failures caused by nozzle clogging, the printer should be stopped and repaired soon after the clog occurs. From the observations, sometimes the printers ran without extruding any material to the end of the programmed printing process, which wasted a large amount of energy.

The impacts of user’s experience level and printing settings on fabrication failures of FDM were analyzed.

4.3.1 Impacts of User's Experience Level

It is expected that a user with a higher experience level is less likely to make failed prints. Therefore, data were analyzed to show the relationship between user's experience level and failure rates. Table 11 shows the summary of the collected data, which includes the failure rates caused by designer error, operator error, overall failure rates and number of users for each experience level respectively.

For designer errors, failures rates decreased as more CAD projects had been done. The failure rates of designer errors also decreased as more parts had been printed. Higher print frequency increased the failures rates of designer errors. For the year of study, the failure rate of juniors (3^{rd} year undergraduates) were four times as much as that of senior (4^{th} year undergraduates) and higher. Therefore, design experiences gained in CAD projects, previous printed parts and knowledge learned from class could decrease the fabrication failures caused by designer errors. Without such experience and knowledge, higher print frequency does not benefit designers.

Table 11 - Summary of User's Experience Level vs. Failure Rates

Category	Experience Level	Failure Rates (%)			# of Users
		Designer Error	Operator Error	Overall	
Number of CAD Projects	<3	9.5	23.8	52.4	21
	3-5	9.1	13.6	36.4	22
	6-10	27.3	9.1	45.5	11
	>10	4.9	17.1	36.6	41
Number of Parts Printed	0	10.0	0	30.0	10
	<5	14.3	14.3	32.1	28
	6-10	5.9	11.8	41.2	17
	>10	7.5	25.0	50.0	40
Print Frequency	<4/semester	6.4	10.8	27.0	37
	1-3/month	12.5	31.3	68.8	16
	1-3/week	4.5	9.1	18.2	22
	>3/week	15.0	25.0	70.0	20
Year of Study	Freshman	50.0	50.0	100	2
	Sophomore	0	25.0	50.0	4
	Junior	43.5	21.7	34.8	23
	Senior and higher	10.6	13.6	40.9	66

Not all parts printed were created by students themselves. Some users downloaded parts designed by experts from websites such as GrabCAD.com and Thingiverse.com. It was expected that failure rates for parts designed by experts would be lower than parts designed by novice designers. Among the 95 prints, 26 parts were CAD files downloaded from the internet. The other 69 parts were created by students themselves. The students were considered to be novice designers, as they do not have a large amount of design experience. From calculation, the failure rate for novice parts was 44.9%, and for expert parts was 26.9%. Therefore, parts created by users with higher level of design experience are less likely to fail. An ANOVA was done for the source of part. However, the p-value is 0.22, which shows no statistical significance.

Improper part geometries could lead to fabrication failures. When designing the parts, the designers should have ideas of the printer specifications, including resolutions and tolerances. If the designed feature sizes are too small based on the given printer resolutions, the features cannot be printed. If the designers do not consider the tolerances of the printers, they may create mating parts with same size and have risks that the parts cannot be assembled. In addition, the design should avoid large, flat areas since they tend to warp. From the observations, there were four failures caused by loose calibration, but these could also have resulted from part geometry issues, since all four parts had large and flat areas.

To reduce the fabrication failures caused by part geometry issues, designers should know the printer specifications. If possible, test parts with different geometries and feature sizes could be printed in order to have a deeper understanding of the printer's capacities.

For operator errors, the failure rates did not change significantly with the number of CAD projects done. The number of CAD projects relates to users' design experience, which should not impact the operator experience. The failure rates decreased as the year of study increased. In addition, the failure rates increased with more parts printed. The failure rates did not change significantly with higher print frequency. These two observations were misaligned with our expectations.

An ANOVA was done for the statistical analysis of the experience variables impacting the failures rates. However, no statistical significance was shown for the results. The p-value for CAD experience is 0.20, for parts printed is 0.10, for printing frequency is 0.28. The result for year of study is not a full rank (rank deficiency), which means the right observations to fit the model are not in the data.

4.3.2 Impacts of Printing Settings

A set of optimal printing settings is expected to be determined when using Ultimaker 2+, which can minimize the failure rate. To figure out the optimal settings, the layer height, infill density, infill pattern, print speed, support material settings and build plate adherence type were investigated.

Figure 13 shows the failure rates versus four different printing parameters: layer height, infill density, print speed and support overhang angle. The support overhang angle is the maximum angle of overhang structure for which support material is added. The smaller the angle is, the more the support material is added. From the diagram, the failure rates increased with larger layer height. The infill density did not show an obvious relationship with the failure rates. When the print speed was at 50 mm/s, the failure rates were at the lowest point. The failure rates increased with higher support overhang angle.

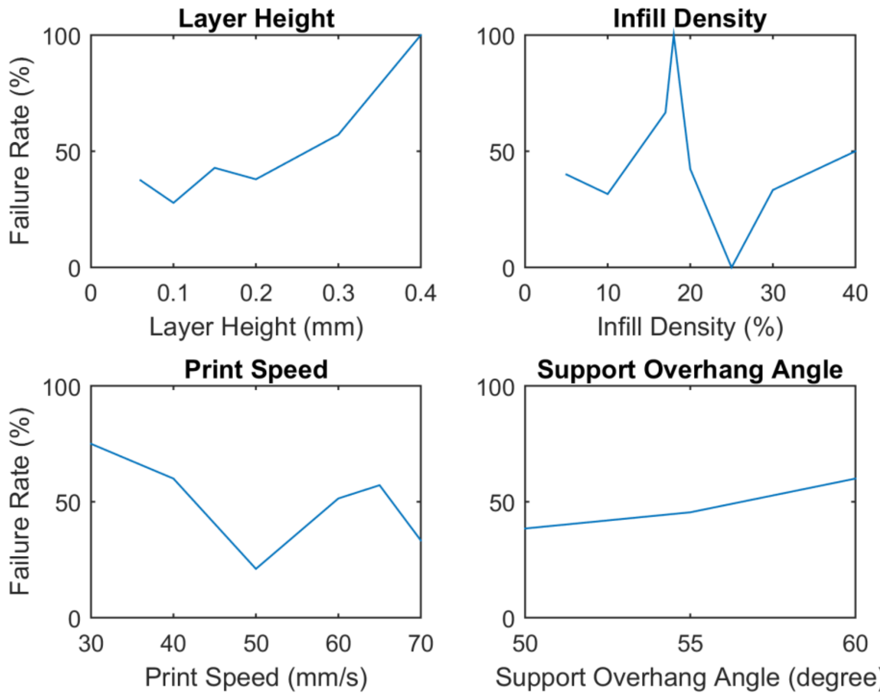


Figure 13 - Failure Rates vs. Printing Parameters

For the infill pattern, the failure rates for Cubic was 28.6%, for Lines was 50.0%, for Grid was 50.0%, and for Triangles was 50.0%. Therefore, the infill pattern did not have a significant influence on the failure rates. For the build plate adherence type, the failure rates for Brim was 21.8%, for Raft was 100%, for Skirt was 76.9%. Therefore, to decrease the failure rate, Brim could be chosen as the build plate adherence type.

An ANOVA was done for the impacts of printing settings on the failure rate. However, no statistical significance was shown for the results. The p-value for the layer height is 0.30, and for the support overhang angle is 0.65. The results for infill ratio and printing speed are not full ranks, which means the right observations to fit the model are not in the data.

4.4 Discussion

From the three sets of ANOVA, no statistical significances were shown. The hypothesis that failure rates decrease if users' amount of experience increases was tested. Based on the analysis, it does not seem that experience results in effective expertise; thus alternative hypotheses are:

- Increased affordances in shops can reduce failures.
- Dedicated training for operating FDM can reduce failures.
- Design for FDM education can reduce failures.

To test the hypotheses, the deliberate practices which is a special type of experience should be measured in order to evaluate the expertise level of users. In addition, the skills in a specific domain cannot be learnt from studying other subjects, it must be studied and practiced in its own way [142]. Therefore, the skills in design for manufacturing cannot be learnt from design activities or manufacturing activities. Individuals should put deliberate effort in practicing design for manufacturing activities.

Based on the observations in the makerspaces, users with less operation experience tended to seek assistance from trained staff. On the contrary, users with more printing experiences tended to work independently. The assistance provided by staff is a type of noise to the measurement. In the future, the assistance should be measured in order to quantify its impact on the failure rate.

Although the results do not show any statistical significance when analyzing the experience and printing factors influencing failure rates, the results do show that human behaviors can affect the environmental impacts of FDM. The fabrication failures caused by human errors accounted for 26.3% of the total number of prints, which increased the environmental impacts by around 35%. The calculation methodology for the environmental impact is presented in our previous work [18]. Therefore, solutions should be provided to decrease the failures caused by human errors. Education, training and assistance provided by software tools could be solutions [190].

4.5 Summary

This study investigated three types of failure causes for FDM, which are the designer error, operator error and machine error. Ninety-five data points were collected, with a failure rate of 41.1% observed. For the 39 failed prints, nine were caused by designer errors, sixteen were caused by operator errors, and fourteen were caused by machine errors. The detailed failure causes are reported.

The impacts of users' experience levels and printing settings on fabrication failures were investigated. Parts created by users with a higher level of design experience had lower rates of failure, but were not statistically significant or statistically different from the general population's failure rate. Therefore, there is a need to distinguish between experience and expertise. Students can gain design expertise through CAD projects, designed parts and knowledge learned in class, but must increase their skill deliberately and with adequate supporting information. For operators without training, the failure rates did not decrease with quantity of printing experiences. For the printing settings of Ultimaker 2+ printers, a small layer height, a small support overhang angle and a print speed at 50 mm/s should be adopted to reduce failure rates.

ANOVAs were done to test the influence of users' experience levels and printing parameters on failures rates of FDM. However, no statistical significances were found from the results. The types of experience measured are not sufficient to explain the failure rates. Therefore, more work should be done to understand actual variables affecting the failures rates of FDM and human behaviors. Nevertheless, the results still demonstrate that accounting for human behaviors is critical when estimating the environmental impact of products.

Chapters 3 and 4 show that novices can make improper decisions. Therefore, they need instruction to reduce fabrication failures. In addition, significant amounts of fabrication failures are caused by machine errors in AM. AM is a CAM process, which is similar to CNC machining. In the future, AM and SM could be combined. Unlike AM, almost all failures are caused by design errors for CNC machining. Chapters 5-7 discuss the failures for CNC machining in order to develop automated guidance software to assist novice engineering designers in making design decisions. This guidance framework could also be applied to AM.

CHAPTER 5. COMMUNICATIONS BETWEEN DESIGNERS AND MACHINISTS FOR CNC MACHINING

5.1 Overview

Novice engineering designers may make improper decisions that unnecessarily increase manufacturing costs and fabrication failures, leading to higher environmental impacts. Manufacturers could provide feedback to novice designers to assist them to modify their parts in order to increase the manufacturability of the parts.

However, differences in interpretation between designers and manufacturers can result in mistakes or miscommunication in the design or processing stages of development. Therefore, it is necessary to identify the possible points of communication failure between manufacturers and designers. To identify the communication problems, observations of communication processes between designers and manufacturers, and interviews that asked them to explain their experiences in communication failures were conducted.

In addition, the effective feedback strategies used by the manufacturers should be identified. The manufacturers observed were machinists in a university machine shop who are experts in assisting novices. The manufacturers review manufacturing requests submitted by students from different majors in the university, provide design feedback based on the submitted drawings or CAD models, and manufacture these parts for students. Therefore, observing the manufacturers can help researchers identify the effective approaches they use to assist novices.

The designers and manufacturers observed and interviewed are primarily working on conventional manufacturing processes, which is mostly machining. Therefore, this chapter focuses on communication problems and effective feedback strategies for machining processes.

5.2 Methodology

5.2.1 Observations in the Machine Shop

Observations were done in a free-access university machine shop to collect data for CNC machining. The free-access machine shop is run by professional machinists. The machine shop is open to all students in the university and does not charge for labor. The designers need to provide raw material to the machine shop. If the manufacturing processes need any special tooling such as drill bits, the designer also needs to purchase these and provide them to the machine shop.

The observations and data collection were conducted during normal operation time, which is 7 am to 4:30 pm on weekdays. Novice engineering designers communicating with machinists were observed and recorded using a camcorder and observation notes. The two machinists observed were experts in assisting novice engineering designers. The novice designers observed were undergraduate and graduate students from different majors in the university. Interviews of designers were done after the communication in order to determine the designers' expertise and experience level and to figure out the effective communication strategies perceived by the designers. After the observation and interview were done, the topics and issues mentioned in the communication were coded. In addition, the artifacts used were coded for each communication.

5.2.2 Interviews with Designers and Machinists

To further collect data for CNC machining, interviews were conducted with designers and machinists who need to fabricate parts using CNC machines. The interview subjects were novice designers and machinists working with novices. The interviews were designed as non-directive/unstructured. The interviewees were asked if they faced any communication problems before, and if so, to describe them. The interviews were audio recorded. In addition, quotes from the interview related to fabrication failures and feedback were extracted and coded into topics. All data collected during observations and interviews was done so with informed consent through an IRB approved protocol. The participation was voluntary and without compensation.

5.3 Results

5.3.1 Observation Results

Thirteen sets of observations were conducted for the pilot study. For the pilot study, only observation notes were recorded for each communication. For the formal study, 16 sets of observations were conducted in the university machine shop. From these 16 observations, ten novice designers were in mechanical engineering major. Six novice designers were undergraduate students with one freshman, one junior and four senior students. Ten novice designers were graduate students. For manufacturing experience, three designers had no experience and had not taken any courses in manufacturing.

Eleven designers had prior experience in machining. For design experience, three designers had not taken any courses in design. All 16 designers had some prior design experience.

For the general communication processes, the designer came to the machine shop and talked to the machinists to get feedback on their designed parts. The machinists reviewed the documents, such as sketches/drawings/CAD models. If the machinists had any confusion about the features or dimensions, they asked the students for clarification. The machinists also provided feedback on how to select tolerances, problematic dimensions and features, design revision suggestions and lead time.

Preliminary interviews were done with the two observed machinists. They were asked to identify the most important information they need to check for in the submitted jobs. Both machinists said that they need to check the geometries of the part, the tolerance values and material type, in order to determine if the part is at risk for failures during manufacturing.

Table 12 shows the topics mentioned during the communication observations. The quotes from the communications are shown in Appendix A.1. These topics were mentioned since the machinists identified some problems when reviewing the manufacturing requests; or the designers asked the questions for feedback. Therefore, this table also represents the failure reasons and problematic features the machinists identified when working with novices.

The most important topic that appeared in the observations was the part features/dimensions clarification. The most common issue was that the drawings or sketches did not have notations of all dimensions for the parts. Therefore, the machinists needed to ask the designers for clarification. In addition, the machinist would confirm the drawing scale, unit system and surface finish with the designers if the information was not provided.

Material is another important topic. When the novice designers approached the machinists for design feedback, most of them had material selected. Therefore, the machinists needed to confirm the material selection with the designers. When the machinists were not familiar with the provided material, they asked the designers about the properties of the material. Sometimes, they also tested the material to learn its properties. In one observation, the designer wanted the machinist to cut a piece of "glassy carbon" using wired EDM. In order to learn about the conductivity of the material, the machinist tested it with a multimeter. The result showed that the material was conductive. Then, the machinist told the designer they could use wired EDM for it. Sometimes, the novice designers did not have material selected and asked the machinists for suggestions. In order to provide feedback, the machinist asked the designers about the functionalities of the parts. Then, the machinists suggested material selection while considering manufacturability, corrosion resistance, mechanical properties and cost of that type of material.

For tolerances, only three observations mentioned this topic directly; however, four out of the remaining 13 observations mentioned the assembly and mating pieces, which is related to tolerance determination. From the observations, the novice designers usually did not know how to determine the appropriate tolerances. The machinist usually determines the tolerance values based on the number of decimal places for dimensions annotated on the drawings. If the machinist finds any tight tolerance such as dimensions with three decimal places, they would ask the designers “I need to know why you [need precision to] three decimal places here.” or “what is the tolerance?” For all three observations that mentioned tolerances, the designers answered “I don’t know” for the questions. Therefore, the machinist needed to explain the meaning of different tolerance values to the novice designers. For other cases, the machinists determined the tolerance requirements by asking the novice designers for more information about mating parts. If the novice designers had the mating parts with them, the machinist would ask the designer to leave the mating parts with them in order to make sure the parts could be assembled.

In addition, the machinists often explained the manufacturing processes and manufacturability of part features, and provided redesign suggestions to the novice designers. From the interview data, it was ascertained that the novice designers could understand what the best manufacturing process is to make the parts, what the machinists can and cannot do, and how to make parts more practically for manufacturing by knowing these types of information.

The last important type of feedback is the job submission, pick-up process, and lead time. The machinists need to explain how to submit job requests and confirm the lead time with the novice designers in order to avoid any delays for the job.

Table 12 - Topics Mentioned during the Communication

Topics/Participants	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	#	Pilot #	Total #
Job submission/pick-up process	x		x	x	x		x	x			x		x	x	x	x	11	4	15
Features/dimensions clarification	x	x			x	x	x	x			x	x	x	x		x	11	5	16
Material			x		x	x	x	x				x	x	x	x	x	10	2	12
Lead time	x	x	x	x			x			x	x		x	x			9	5	14
Manufacturing processes	x	x		x			x		x					x		x	7	8	15
Assembly/mating pieces		x						x		x					x	x	5	5	10
Process/Machine/tool selection		x				x			x					x		x	5	2	7
Manufacturability		x										x		x	x	x	5	1	6
Redesign/part modification		x									x	x				x	4	2	6
Quantities of parts	x	x										x				x	4	1	5
Tolerance					x		x			x							3	6	9
Hole			x							x						x	3	5	8
Fixture		x				x											2	0	2
Drawing scale			x														1	0	1
Clearance			x														1	0	1
Unit system					x												1	1	2
Surface finish													x				1	1	2
Feature function		x	x				x	x		x	x		x		x		8	2	10

Table 13 - Artifacts Used for Communications

Artifact/Participants	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	#	Pilot #	Total #
Physical parts/blanks	x	x	x	x		x	x	x			x	x	x			x	11	6	17
Drawings	x		x		x		x				x	x		x		x	8	7	15
Online portal	x	x			x		x	x			x		x				7	6	13
Sketches			x					x				x	x				4	4	8
CAD model										x							1	4	5
Ask for CAD model			x		x							x		x	x	x	6	1	7

Table 13 shows the artifacts used by the novice designers and machinists for the communication. During the communication between the novice designers and the machinists, 11 out of 16 communications (17 out of 29 total communications) used physical parts or blanks. From the feedback provided from the interviews, three novice designers mentioned the most valuable feedback strategies during the communications were communicating using physical parts.

Eight out of 16 observations, and seven out of 13 pilot observations used drawings during the communication, which shows that drawings are still the primary form of communication between the novice designer and the machinist. For these observations, the novice designers brought their drawings to the machinists for feedback, mostly because they thought it would be the best form to communicate their design. However, the machinists thought the CAD model was more important than 2-D drawings. The machinists asked for CAD model files in six observations. According to the machinists, they need the CAD models, since if the dimensions are not specified in the drawings, they could check the CAD models to obtain the values. If the designers did not bring any drawings or CAD models for simple parts, the machinists would help them to make sketches to deliver their design intents.

This machine shop used an online portal to manage the job requests. By using this online portal, the machinists are able to collect the information of the designers such as their education level, major and contact information. The designers can also specify the quantity of parts, material type and work description using this online portal. By using the online portal, the machinists could manage the requested jobs more effectively and collect information that cannot be shown in the drawings and CAD models.

5.3.2 Interview Results

Four interviews were conducted, three with machinists and one with a novice designer. Interviewee 1 (Designer) was a design engineer who worked with manufacturers a lot. He described his process during the design phase and some of the challenges that he faces. One of the first points he made was that he does not really care about the manufacturing process chosen by the machinists and tries not to interfere, as long as dimensions and tolerances are met, and the functionality of the part is maintained. However, he also mentioned that it is beneficial if manufacturers know the application of the part, as this helps them understand what the constraints are for.

The designer also emphasized that the choice of manufacturers plays an important role during the design and manufacture process, as some manufacturers actively ask for more information if things are ambiguous while others do not. He gave an example of a round orifice plate he had designed, where he did not explicitly mention that the hole in the plate was concentric with the plate. The manufacturer chose to interpret this as the freedom to put the hole anywhere on the surface of the plate, which reduced the functionality of the plate. He also mentioned that some machinists do not care about standards, and certified people are required to build certain parts because of these standards.

The designer described his process when he has to make design changes. He mentioned that through his experience, he has learned what manufacturers are looking for. He points out important features to them and takes images of various views. This designer uses phone calls and emails primarily to communicate with manufacturers, but sometimes does need to physically meet with them.

For drawings, he mentioned that his "mind can drift off while making engineering drawings" because it is not a stimulating process for him, and it takes a lot of time. However, he mentioned that making drawings is also an important process for him, as he might think of redesign ideas when making the drawings.

The key takeaway from this interview was the need to eliminate ambiguity. Ambiguities can arise regarding material choice, surface finishes and from incomplete dimensioning.

Interviewee 2 (Machinist 1) was an experienced machinist, who spoke about his experiences during interactions with designers and the challenges he faces. He highlighted that most of the problems he faces with CAD models and engineering drawings are due to a lack of experience on the designer's side. He also mentioned that it is difficult to solve communication problems without having all the information about how parts go together.

According to Machinist 1, machinists may or may not "proactively reach out with questions", depending on their relationship with designers, since this process is time consuming. He also brought up another issue regarding measurement units used by designers. Designers tend to make CAD models/drawings in metric, but then ask machinists to convert dimensions to imperial units and manufacture parts. This sounds reasonable in theory; however it might not be so in reality as it could lead to problems with ordering non-standard pieces of material or require special tooling.

Machinist 1 also mentioned that he has had problems with incorrect or incomplete geometric tolerances, which has led to flatness issues in parts. He also said that some designers "do not have the concept of lead time," as novice designers do not understand the fact that there is a time lag wherein raw material needs to be ordered and received.

Interviewee 3 (Machinist 2) was another experienced machinist who provided further insight into the manufacturing process and the challenges he faces. One of the key points he made was that a lot of machining processes (like CNC, waterjet) are done through CAD models directly. However, 2D drawings are also necessary to "put in the hands of the machinist", so that they know additional information, like tolerances and pin fits, and do not need to measure these from the CAD model. Drawings are also important for inspection checks.

Machinist 2 also mentioned that "machinists do not want to be in a liability situation", so they try to stay "ahead of the curve" and "figure out the application" of the part. He extended this further to his unwillingness to handle expensive pieces of material, if he is unsure of his process capability to support the project. He emphasized that he would rather "lose business than damage this expensive piece of material".

Some of the communication problems faced by Machinist 2 are due to "language" barriers. He mentioned that he sometimes has to "draw things to ask questions". This indicates that he has to resort to visual prompts to get his point across to some designers.

He asks questions about CAD models feature-by-feature. However, some features could get overlooked, due to time constraints.

Machinist 2 also spoke about the importance of standards. He highlighted that different vendors have their own different standards, based on their capabilities. He mentioned that some designers do not follow standards set by the manufacturer. As a result, he has to make changes to drawings to match these standards, which is time consuming.

Interviewee 4 (Machinist 3) was an experienced machinist working with college students. The machinist in the university machine shop wanted CAD files, since if there are any dimensions missing in the drawings, they can measure the CAD model to get the dimensions. However, not all students know how to create CAD models, especially students not in ME/AE. It is a struggle for some students to model or specify threads, especially if they flip back and forth between metric and imperial systems. Machinist 4 also mentioned the tolerances. The students may specify tight tolerances or even omit tolerance information completely on the drawings.

For the communication process, when a student brings in a part, the machinist will first ask about the materials. The machinist will provide suggestions based on the functionality of the part. Then, he will look at the geometry to ask the students if they need some specific low-manufacturability features. A documentation system is needed to record the comments. Otherwise, it could lead to something that does not work.

Based on the above four interviews, there are a few reasons for gaps or loss of information between the design phase and the manufacturing phase.

1. The inexperience of the designers themselves: novice designers may not be able to communicate their ideas effectively to machinists. They are not well versed in how to dimension drawings, which could lead to missing dimensions or dimensioning critical features off unimportant sides or edges, ultimately resulting in parts not meshing together. They are also not mindful of tolerances, maybe due to a lack of understanding of the application of the part, sometimes imposing three or four decimal place tolerances when they are not required. Such tight tolerances increase the cost and manufacturing time of parts.

2. Proactivity of manufacturers to gather additional information: Efforts taken by machinists to understand the application of a part and to help novice designers with revisions contribute to reducing ambiguity and maintaining functionality of parts.

Table 14 shows the topics mentioned in the interviews. The exact quotes extracted are shown in Appendix A.2. The most common topics leading to fabrication problems are tolerances, dimensions, and hole callouts. The interviewees mentioned that designers do need to have manufacturing knowledge to do better design.

Table 14 - Topics mentioned in the interviews

Topics/Interviewee	Designer	Machinist 1	Machinist 2	Machinist 3
Tolerances	x	x	x	x
Dimensions	x	x	x	x
Hole callouts	x	x	x	x
Surface finish	x	x		
Pin fits		x	x	x
Feedback system	x	x	x	x
Drawings	x	x	x	x
Designers need to have manufacturing knowledge	x	x	x	x
Experience of designers	x	x	x	x
Design revisions	x		x	x
Material cost		x	x	
Processing cost	x	x	x	

For the tolerance, all three machinists mentioned they faced situations in which designers put tight tolerances but did not really mean to do so. For example, Machinist 3 mentioned that a student came to him and said he wanted the tolerance of 0.0005 mm. He said he did not have a machine that can do this many decimal places. Then, the student checked with his advisor who said they did not need the 0.0005 mm tolerance. For another case, the machinist found that the drawings had four decimal places. He asked the student why it needed to a four decimal points. The student did not understand why he asked that question. The student put the four decimal points because they had it default to that level of precision in SolidWorks.

From the interviews, the hole callout is another factor that contributed to failures. The common failure is that designers are confused about threaded holes and clearance holes. The threaded hole is a hole with threads. The clearance hole is a hole that is big enough for a threaded screw to pass through. Machinist 3 also mentioned that he needed to explain to the students that he cannot do a square hole with a round tool.

5.4 Discussions

From the observations and the interviews, the most common failures during communication are identified, which are missing information, unclear information, tight tolerances and low manufacturability features (i.e., features that cannot be made from conventional machining, such as square holes and holes with flat bottoms).

From the observations in the machine shop, effective strategies used by the machinists can be identified. For missing information and unclear information, the machinists could identify the problems and ask the designers to clarify the information. If the designers have problems providing the information, the machinists could assist them to identify the information by understanding the functions of the parts.

For determining the required tolerance values, the machinists often pointed to some features they identified to be critical (such as holes) and asked if the dimensions and tolerances of the features were critical for the parts' function, in order to avoid too tight or loose tolerances. They also asked for the mating parts to ensure the parts can be assembled.

For the low manufacturability features, the machinists often pointed to the features and explained why the features could not be made by sketching the manufacturing processes. In addition, if the machinists identified complex part geometries, they asked if the features were necessary for the design in order to avoid over design issues. These data demonstrate that visualization is important for communication.

In addition, although experienced designers like the one interviewed here may only communicate with machinists through phone calls or emails, novice designers think the face-to-face communication is better for them. Three novice designers said the most valuable feedback strategies the machinist used is communicating with real parts. One novice designer mentioned that he had conversations with the machinist over emails; however, face-to-face communication with both parties looking at the same parts was more effective. In addition, the machinist was able to point to the identified problematic features during the communications.

5.5 Summary

This chapter identified the common fabrication failures of machining from interviews and observations of machinists and designers. The most common failures are missing information, unclear information, tight tolerances, and low manufacturability features. Missing information and unclear information, such as dimensions and annotations, could lead to parts manufactured not as the designer intended. Unnecessarily tight tolerances could increase the production time significantly and increase the possibility for failures. Low manufacturability features cannot be made from conventional machining processes and will require special tooling, which also increases the production time, cost, and failure possibilities.

Effective strategies have been identified from the observations in order to decrease failures. Novice designers may not be able to communicate their ideas effectively to machinists. Therefore, efforts taken by machinists to understand the application of a part and to help novice designers with revisions contribute towards reducing ambiguity and maintaining functionality of parts. Visualizations used to point out problematic features and explain the manufacturing processes could assist the novice designers in redesigning the parts. Face-to-face communications using real parts could also assist the novice designers in understanding how to improve the manufacturability of the parts.

These findings are used to develop the novice DFM prototype in Chapter 6.

CHAPTER 6. DESIGN FOR MANUFACTURING PROTOTYPE DEVELOPMENT

6.1 Overview

Chapters 5 identified the common failure points in machining and the effective communication strategies used by machinists who are experts in assisting novices to make design decisions. Based on the identified feedback content and strategies, a DFM prototype for novices was built to provide feedback to designers on paper for machining process, including turning and milling. This prototype can simulate how to assist novice designers to change design decisions to increase manufacturability and decrease fabrication failures.

Firstly, the system framework was developed based on the communication processes used by the communication experts. With the identified system framework, the feedback contents and feedback strategies were identified based on literature, benchmarking studies, interviews, and observation results. In order to develop the novice DFM prototype for testing described in Chapter 7, a pilot study was done. In the pilot study, the participants were asked to test and evaluate different types of feedback content and strategies.

For the novice DFM prototype, SolidWorks is used as the CAD software. Objects are chosen as study cases representing common design issues identified. A SolidWorks plug-in demo was developed to show the general functions of the prototype. For the prototype testing, a paper version of the system was developed.

6.2 System Framework

Figure 14 shows the general framework for the system. The first step in the system is to ask the user to import or create the CAD model in using CAD software, such as SolidWorks. With the CAD model, the system analyzes the design, and outputs the DFM feedback for the users. If the user is satisfied with the feedback that no problematic feature exists, or he/she considers the problems in the feedback as not critical, the user can proceed to the next step. Otherwise, the user could modify the parts based on the feedback provided by the system, and then analyze the part again. This process iterates until the user is satisfied with the designed part.

The next part of the system asks the user to input the design parameters for the parts, such as tolerances and material type. For the tolerance values, the user can input the general tolerances for the whole part, and also the specific tolerances for features that need to have looser or tighter tolerances than the general tolerances. With the input values, the system can evaluate the design and provide feedback to the user. If the user specified too tight of tolerances, the system will explain to the user the meanings of using tight tolerances and confirm with the users that this value is what the user wants. Based on the feedback provided, the user can choose to adjust the tolerance values and evaluate again, or proceed to the next step. For the material type, the user can specify the material selection for the design. The system is able to provide feedback, such as the mass of the part based on the selected material. The system should also explain the manufacturability and mechanical properties of the part. If the user specifies materials that are very difficult to machine, the system will notify the user and make sure the user does need this type of material for the design.

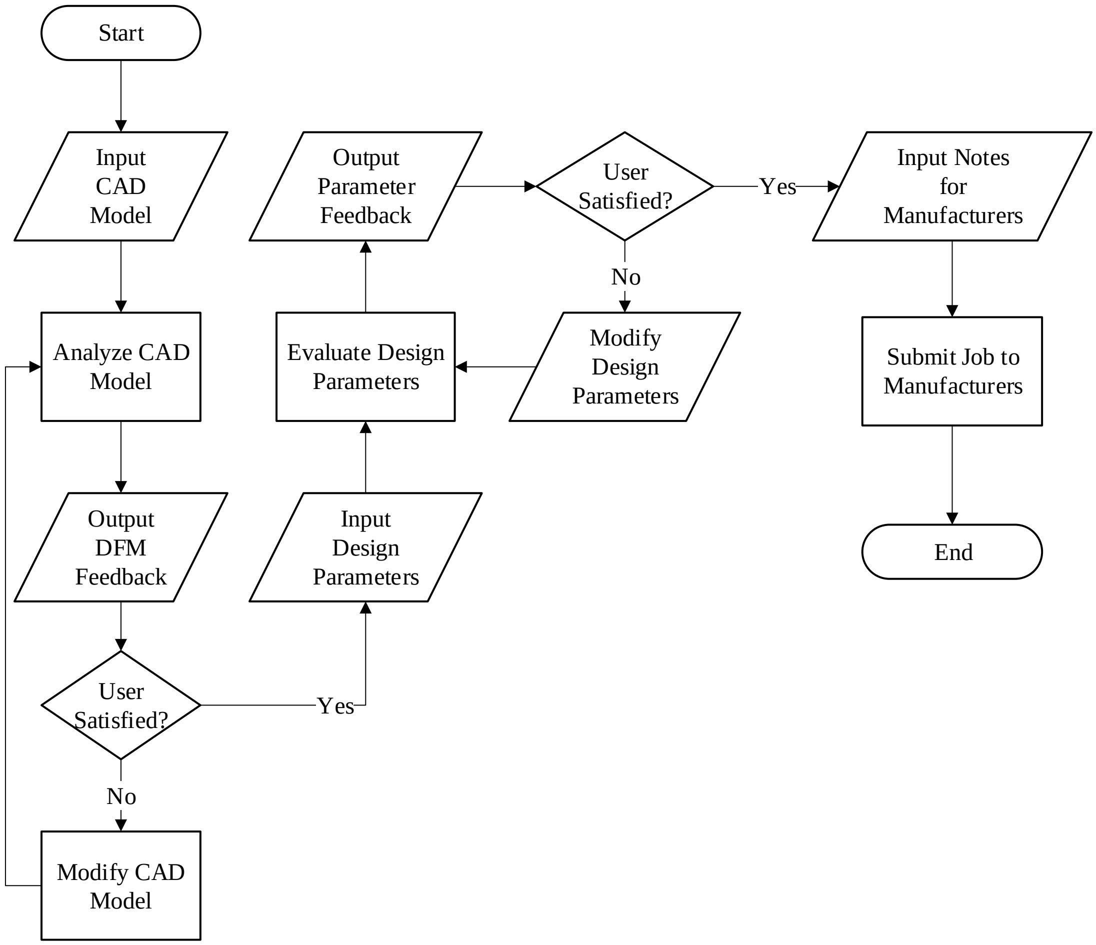


Figure 14 - Prototype Algorithm

After the user decides that he/she is satisfied with the input design parameters, the user can input additional notes for manufacturers, such as surface finish, quantities of parts, and any other special instructions. Then, the CAD model with input parameters and notes is submitted to the manufacturers. With the submitted information, the manufacturers are able to make the parts for the designers.

6.3 Feedback Content and Strategies

With the general framework, effective feedback content and strategies should be identified. Benchmarking of DFMXpress and Xometry have been done to identify effective feedback content and strategies. DFMXpress is a SolidWorks' own analysis tool that identifies areas that might cause fabrication problems. Figure 15 shows the user interface of DFMXpress. The functionality of DFMXpress is limited to four manufacturing processes: mill/drill only, turn with mill/drill, sheet metal, and injection molding. For the feedback, DFMXpress can show the DFM rules failed and passed. For the rules failed, pop-up dialogue explains the failure reasons to the designers when the designers put the mouse on each rule. In addition, the problematic features are highlighted when the designer clicks the "+" next to the failed rules and selects the failed instance. If the designers click the "Help" button, SolidWorks will launch the user manual for using DFMXpress, which describe the DFM rules with example pictures showing high-manufacturability and low-manufacturability features for each rule. This user manual also explains how to configure the parameters of the design rules such as the hole depth to diameter ratios should be less than 2.75. However, the users still need to set the rule parameters by themselves, which makes failure of CAD parts subjective and also requires expertise from the users to use it. DFMXpress does not take material properties and tolerances into account when performing the analysis.

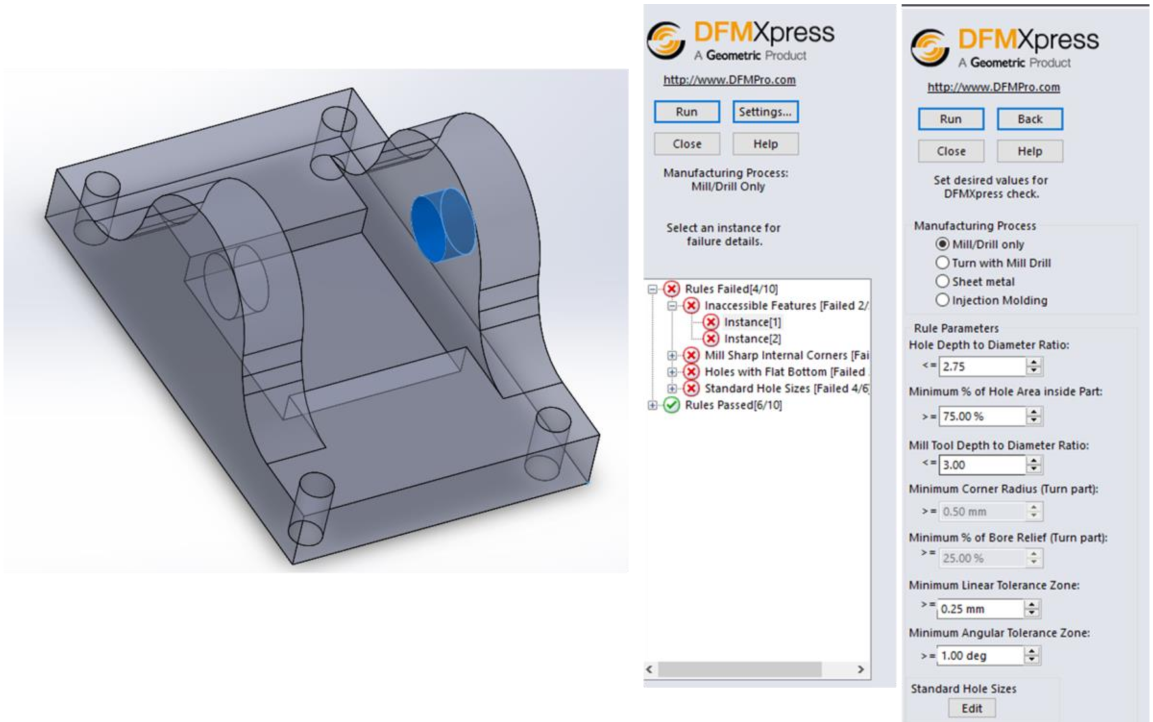


Figure 15 - User Interface of DFMXpress

Xometry is a third-party SolidWorks plug-in that provides instant feedback on design errors, pricing, and lead time. Xometry can manufacture the parts for the designers if designers are satisfied with the quote provided by the system. The user interface of Xometry is shown in Figure 16. Xometry can highlight the problematic features in the CAD model without extra clicks, unlike DFMXpress. Unlike the DFMXPress, Xometry also shows the DFM rules failed. In addition, Xometry allows users to select different material and surface finishes, and input quantities of parts required. After changing the design parameters of the part, Xometry can update price and lead time. However, Xometry does not provide warnings if unnecessarily tight tolerances are set. In addition, the extensive range of materials and manufacturing processes could be overwhelming for novice engineering designers. Moreover, Xometry does not check drawings, which is be a crucial consideration for manufacturing processes.

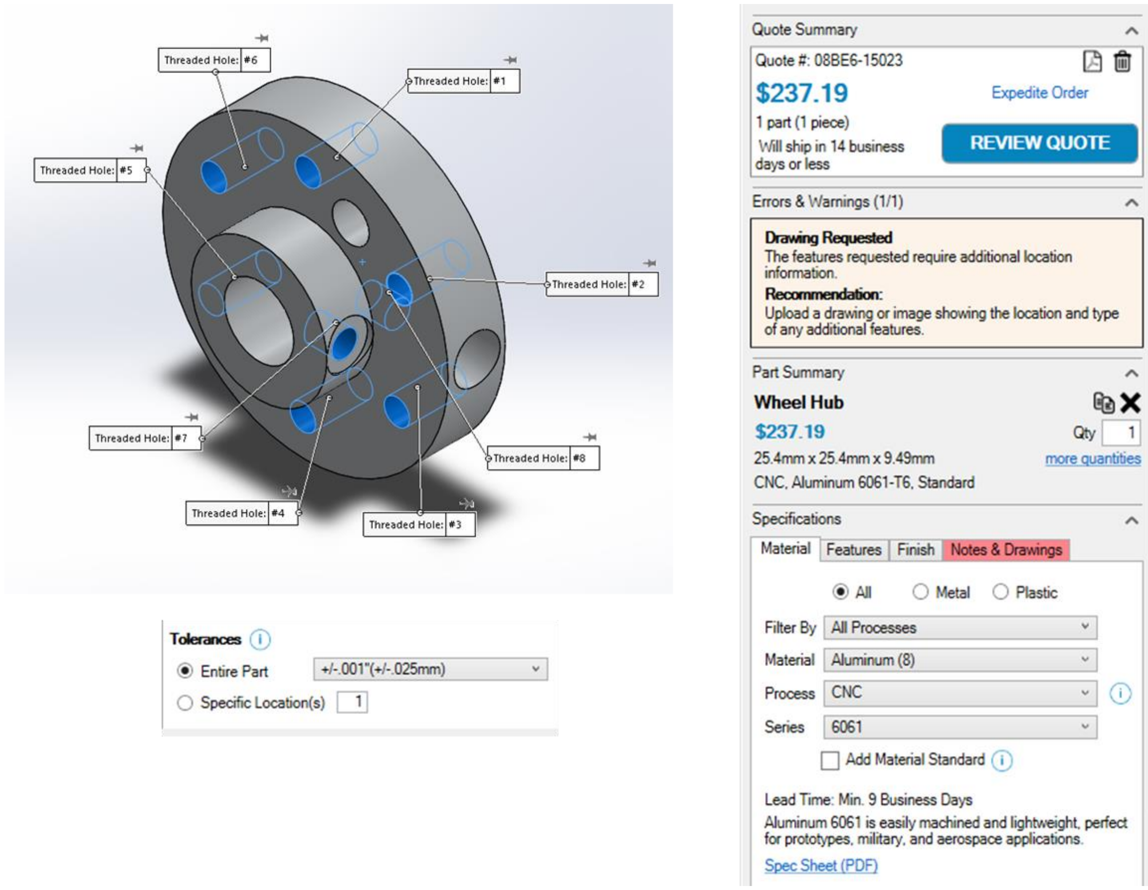


Figure 16 - User Interface of Xometry

From the benchmarking studies, both DFMXpress and Xometry can show the DFM rules failed by the part as designed. From the literature review, DFM guidelines are part of the important feedback content. Existing DFM guidelines for both machining and FDM are summarized from literature. The DFM guidelines for machining are shown in Appendix B.1, and those for FDM are shown in Appendix B.2.

In addition to the DFM guidelines, DFMXpress explains the manufacturing processes with regard to each failed rule. The machinists also explain the manufacturing processes to the designers. In addition, the machinists sometimes also sketch the manufacturing processes when explaining. Therefore, explanations and visualizations of the manufacturing processes could be potentially effective feedback content.

Both DFMXpress and Xometry highlight the problematic features of the CAD model. Highlighting the problematic features is similar to the machinists pointing out the features, assisting the designers to both locate and identify the problems, which may be an effective strategy for the novice DFM prototype. Without such a strategy, the novice designer may not be able to locate the problematic features successfully.

In addition, DFMXpress provides pictures in the help manual to show parts with high and low manufacturability features. Similar to DFMXpress, the machinist used sketching to explain problematic features during the observations. With example parts, the designers are able to not only identify the problems, but also understand how to fix the problems. Therefore, pictures showing examples could be used to assist the designers to make changes.

6.4 Pilot Studies

Explanations and visualizations of manufacturing processes and example parts are potentially effective feedback content and strategies. It is necessary to figure out what type of visualization feedback can assist the designers more effectively. Four types of visualization were suggested, which are manufactured parts from current CAD files, example pictures to show features of high-manufacturability and low-manufacturability, pictures or videos to show the manufacturing processes, and pictures with suggested changes. In order to test which type of visualization can assist the designers more effectively, a pilot study was conducted.

Two parts were selected for the pilot study. The first part is a pawn piece, which should be made using a turning process, shown in Figure 17. The overall dimensions of this part are 15 x 27 x 15 mm. The second part is a mounting piece for a kick-down stopper, which should be made using a milling process, shown in Figure 18. This part is used to mount the stopper piece to a door. The overall dimensions of this part are 75 x 50 x 35 mm. The hole diameter for the four small holes are 5.13 mm. The hole diameter for the two large holes is 10 mm. These two pieces were selected since they both have low manufacturability features and are pieces with functionality. The manufacturability problems existing in these two parts were common failures identified from the interviews and observations.

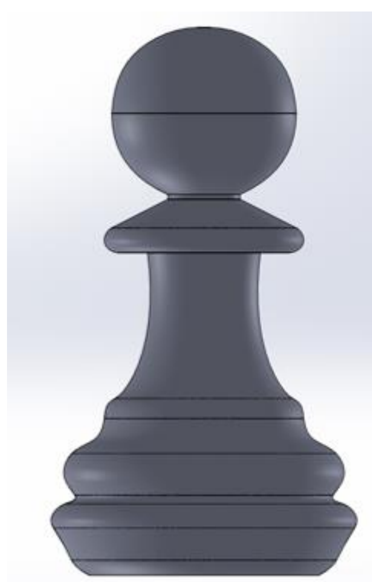


Figure 17 - Pawn Piece

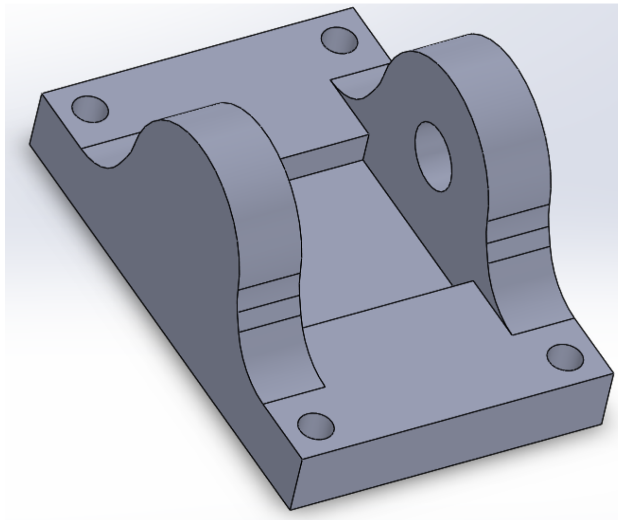


Figure 18 - Doorstop Piece

For the pawn piece, the problematic feature is shown in Figure 19. This overhang feature cannot be made from one turning path due to the angle of the tooling on the CNC machine. Two turning paths are required to make this part. In order to decrease the manufacturing cost and time, a fillet or chamfer should be added.

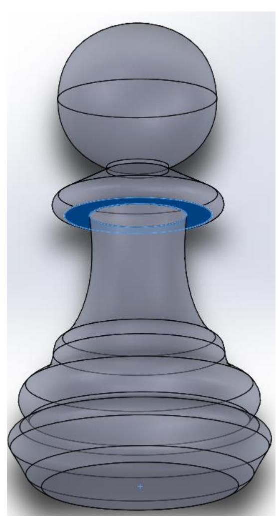


Figure 19 - Problematic Feature in the Pawn Piece

For the doorstop piece, three manufacturability problems exist, which are shown in Figure 20. The first problem is the non-standard hole sizes. The diameter of the four small holes is 5.13 mm, which is not a standard hole size, requiring a special drill grinding. The second problem is the inaccessible features; the two blind holes cannot be easily accessible using conventional machining process. In order to avoid special tooling, features should be easily accessible, and undercuts should be avoided. The third problem is the sharp internal corners, which is also called square hole problem according to the machinists. Sharp internal corners cannot be made using round tooling. In order to avoid special tooling, fillets should be added to the corners.

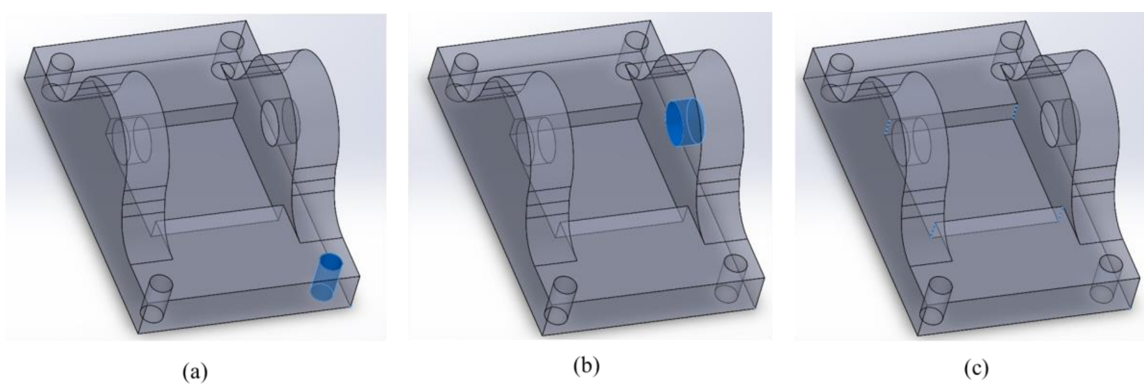


Figure 20 - Problematic Features in the Doorstop Piece

For the pilot study, the participants were asked to modify these two parts based on the provided feedback. They are required to maintain the functionality of the parts. In order to show the functionality of the doorstop piece, Figure 21 was provided to the participants. The covered part is the part they were asked to modify.

Figure 21 - Illustration for Functionality of the Doorstop Piece

For the pilot study, a paper prototype was provided to the participants. Figure 22 shows an example feedback page for the prototype. Each page consists of three parts, which are the feedback context explaining the DFM guideline, original CAD model with the problematic feature highlighted, and the visual feedback. For the DFM guidelines, the terminology or “jargons” used by machinists was minimized, since the novice designers may not understand them, based on the observations.

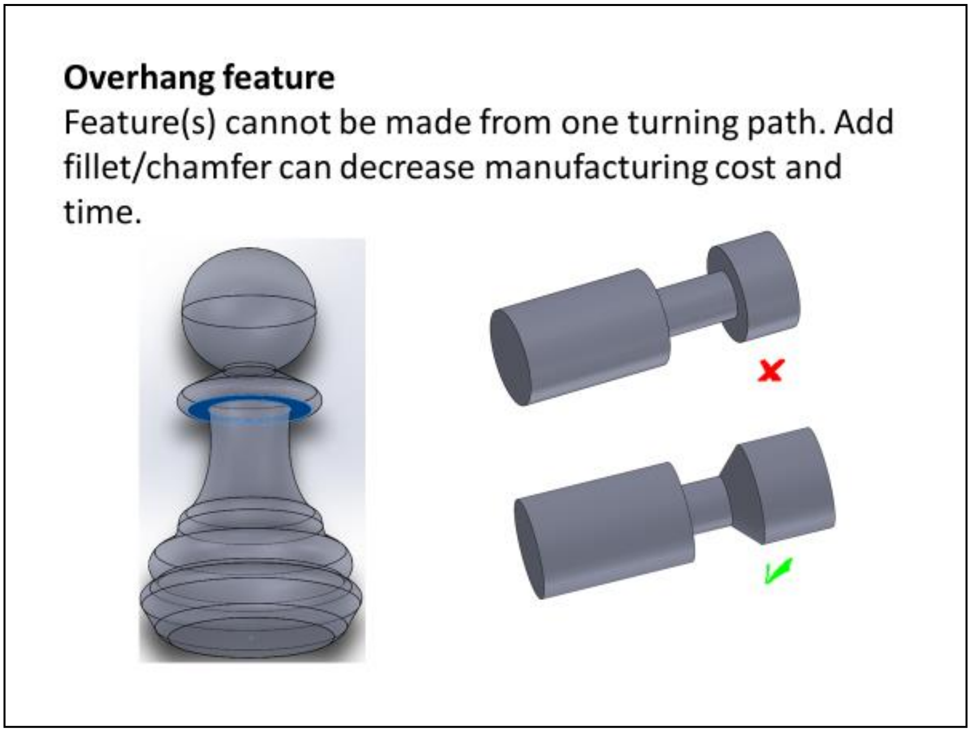
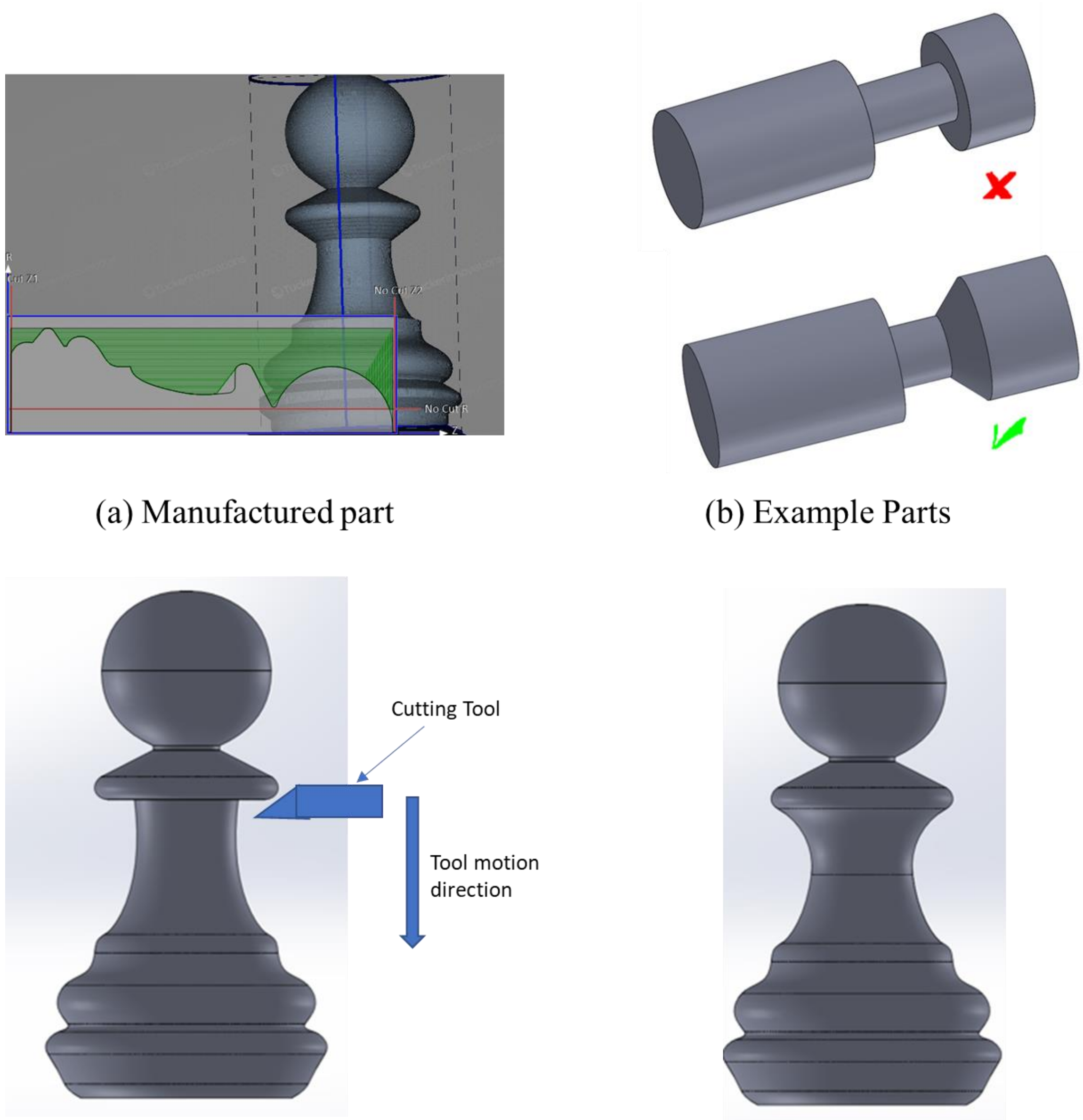


Figure 22 - Example Feedback for the Prototype on Paper

In the pilot study, four types of the visualization feedback were tested. Figure 23 shows the four types of the visualization feedback for the overhang feature of the pawn piece. The manufactured part with tooling path in the left corner was generated using SculptPrint, which is a commercial software application that allows for a high degree of automation in the production of G-code for CNC machines [191]. The example part feedback shows one low-manufacturability feature with no fillet or chamfer for the overhang feature, and one high-manufacturability feature with a fillet. The manufacturing process feedback shows the cutting tool and tool motion direction for the part, which illustrates that the overhang feature cannot be made from one turning path. The suggested changes picture shows the suggested changes for the part. Similar visualization feedback contents were created for the doorstop piece. For the visualization of the example parts, the pictures were adapted from the DFMXpress user manual.



(a) Manufactured part

(b) Example Parts

(c) Manufacturing Process

(d) Suggested Changes

Figure 23 - Four Types of Visualization Feedback

Four sets of pilot studies were done. The participants were undergraduate students who had taken the basic CAD modeling class. Based on the pilot study, the visualization showing example pictures of features with high-manufacturability and low-manufacturability were found to be the most effective method.

From the participants' feedback, the two types of visualization related to manufacturing processes require the designers to have knowledge of manufacturing. From this type of visualization, users can identify the problems; however, they did not know how to solve the problems.

Visualization showing suggested changes is effective for designers who want to have manufacturable parts quickly. However, this type of feedback is prone to mistakes, especially for complex parts.

6.5 Developed Novice DFM Prototype

The novice DFM prototype consists of two major parts: the DFM feedback and the tolerance input. The DFM feedback consists of the DFM guidelines, the CAD model with highlighted problematic features, and the pictures of example parts. An example page is shown in Figure 22.

The tolerance input is included in the prototype because the machinists mentioned during the interviews that significant number of novice designers do not specify the tolerance values for their designed parts. However, tolerance values are important to the manufacturing process, and tight tolerances specified could increase the fabrication failure risk significantly. However, novice designers may not be able to specify appropriate tolerance values due to lack of expertise. Therefore, the machinists usually suggest tolerance values to the designers based on the functions of the parts. To implement this strategy, the users were asked to input the tolerance values using the prototype. The prototype provides recommended tolerance values to the designers. This recommended tolerance value was determined by manufacturing experts. Figure 24 shows the general tolerance input page in the novice DFM prototype. To assist the designers to determine the tolerance values, the overall dimension of the part is also provided.

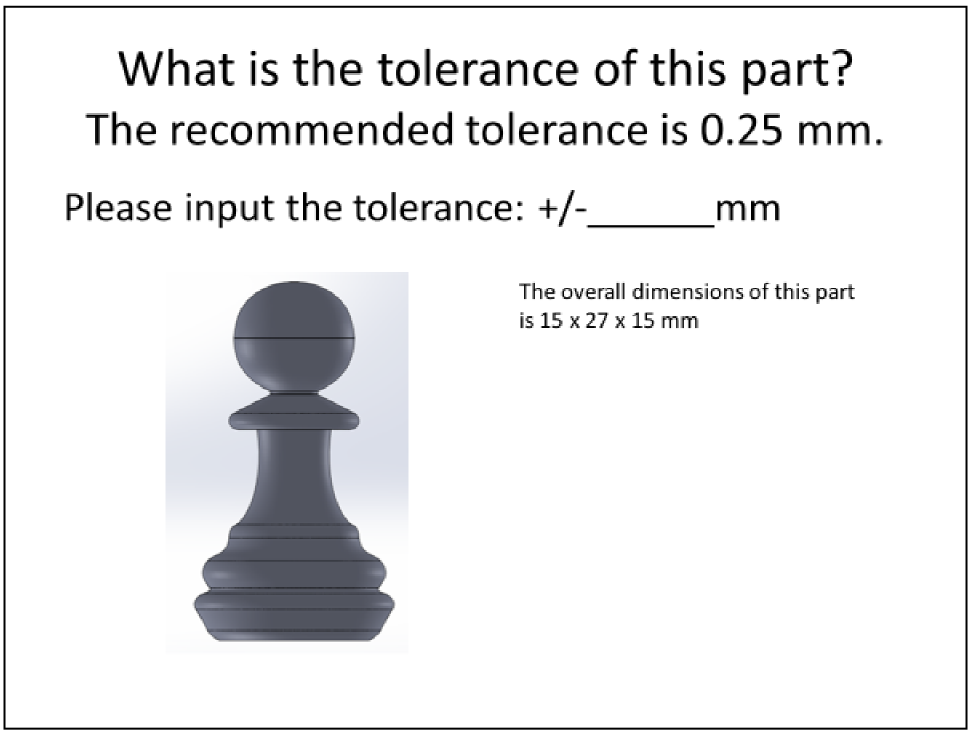


Figure 24 - General Tolerance Input Page

In addition, the machinists usually ask designers if features are critical and require tighter tolerances. To implement this strategy, the novice prototype also asked the same question to the designers. If the designers think any of the features need tighter tolerances, they can highlight the feature and specify different tolerance values. Figure 25 shows the specific tolerance input page for the novice prototype.

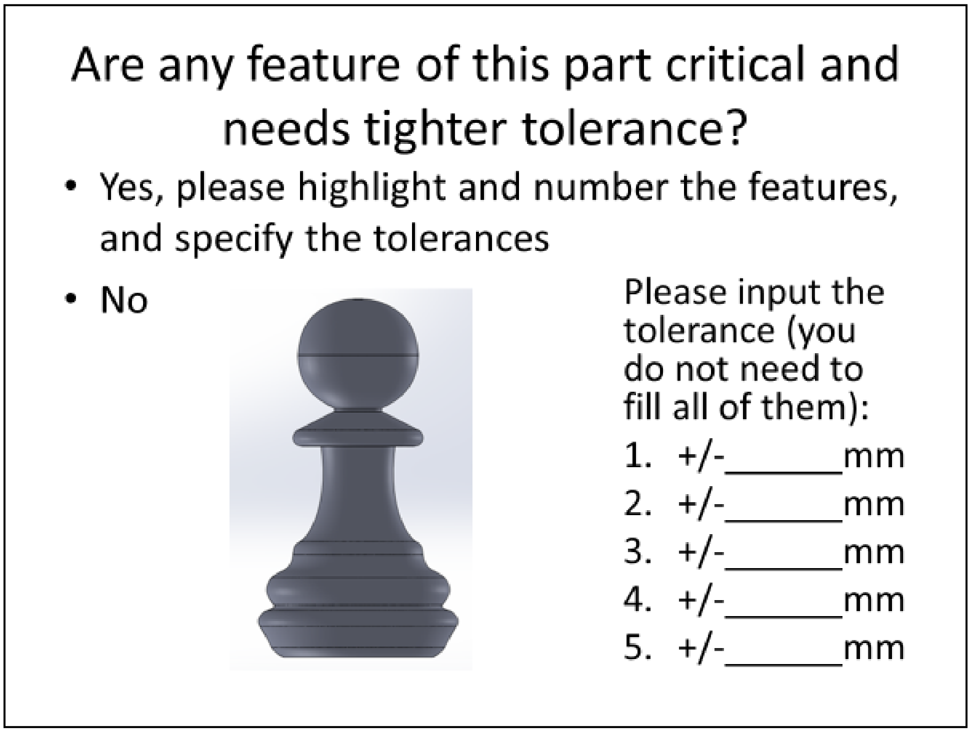


Figure 25 - Specific Tolerance Input Page

A demo of the SolidWorks plug-in for the novice DFM prototype was also developed. The user interface is shown in Figure 26. This demo shows the four parts of the novice DFM prototype, which are material selection, design tolerances input and evaluation, manufacturability evaluation, and additional notes/input for the manufacturers. After specifying the material, this plug-in is able to calculate the mass of the manufactured parts.

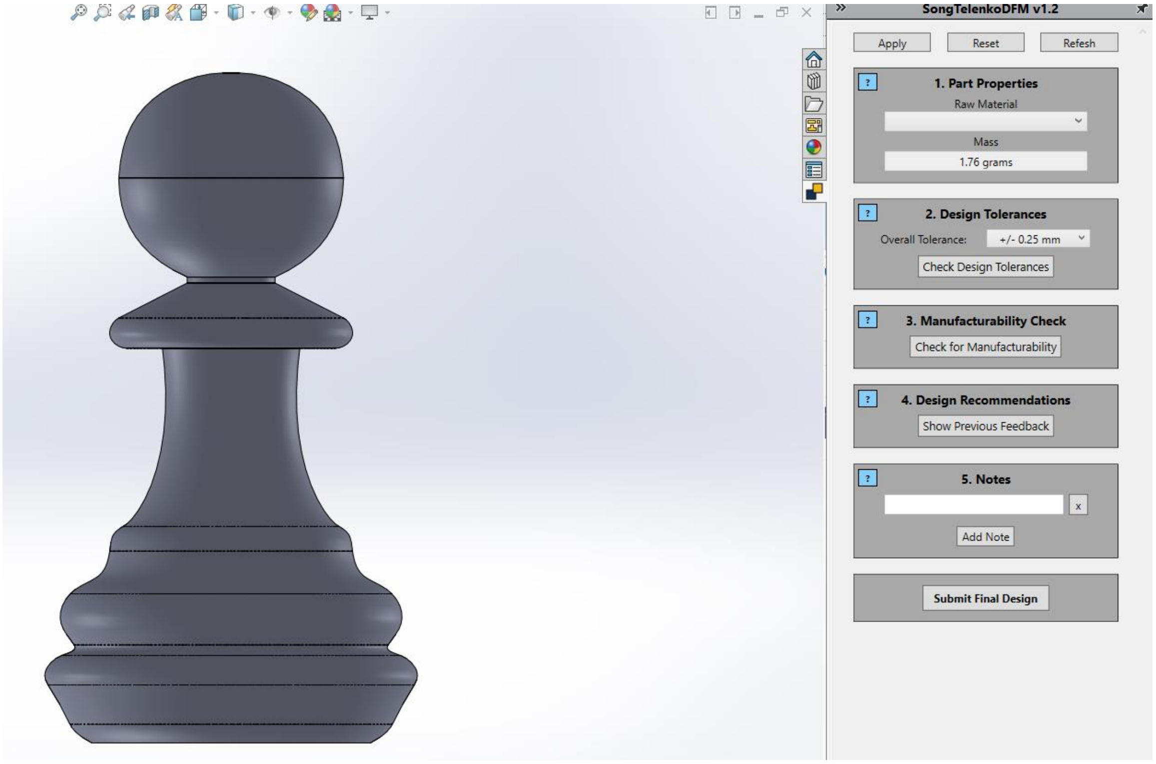


Figure 26 - SolidWorks Plug-In Demo

For the tolerance input, it asks the designer to input the overall tolerance for the part. In addition, the prototype can go through each feature and ask if the designer needs a specific tolerance for the feature. Figure 27 demonstrates the tolerance input using the plug-in.

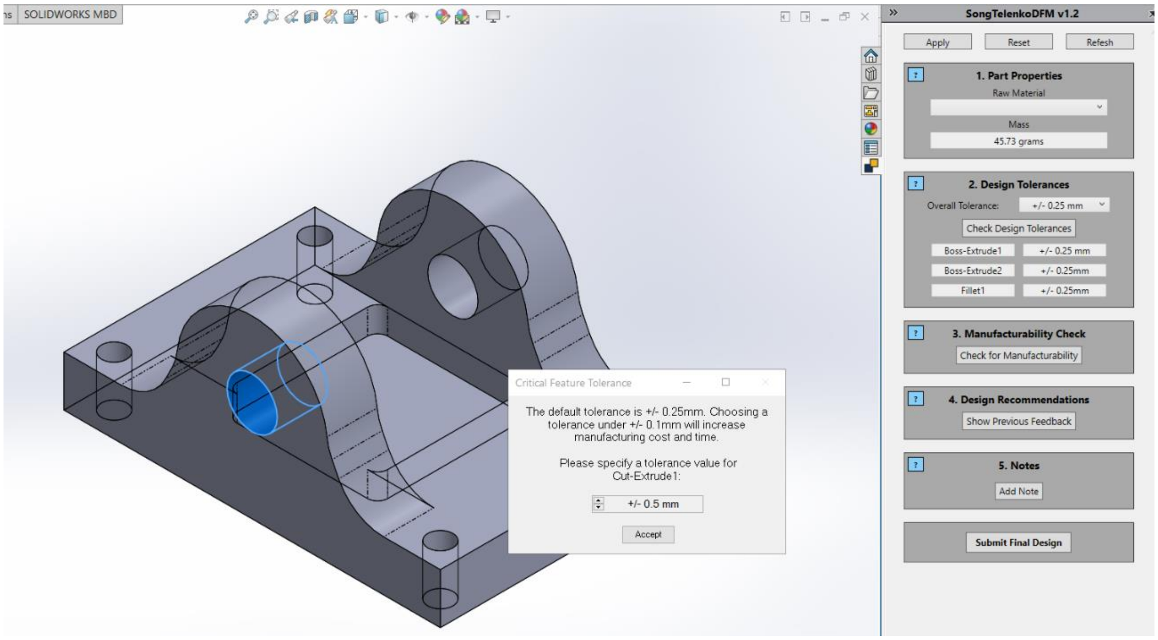


Figure 27 - Tolerance Input for the SolidWorks Plug-In

To check the manufacturability of the parts, the designer needs to click the "Check for Manufacturability" button. Then, the plug-in analyzes the part and shows the feedback to the designer. The feedback consists of a list of failed rules and highlighted problematic features in the CAD model. By clicking each failed rule, the plug-in will show the DFM guidelines and picture of example parts.

After the designer is done with all the modifications and input, the designer will click the "Submit Final Design" button to submit the CAD model and material selection, tolerance values and additional notes to the machinists.

6.6 Summary

Based on the findings from the literature review, benchmarking studies, observations and interviews of the machinists and designers, the novice DFM prototype was developed. The developed DFM prototype can provide manufacturability feedback, including DFM guidelines, CAD model with highlighted features, and example pictures showing high and low manufacturability features. The prototype also requires designers to input overall tolerance values for the part, and any specific tolerances for critical features. To assist the designers to input the tolerances, recommended values are provided to the designers. In addition to the paper prototype, a demo of the SolidWorks plug-in was developed to illustrate the user interface and basic functions of the prototype.

The developed novice DFM prototype on paper was tested. The testing results are shown in Chapter 7.

CHAPTER 7. VALIDATION WITH PROTOTYPE TESTING

7.1 Overview

The novice DFM prototype development was described in Chapter 6. This chapter illustrates the methodology to test the developed prototype. The participants were asked to modify the pawn piece and the doorstop piece using the novice DFM prototype and the benchmarking software DFMXpress. To compare the performance of participants modifying the parts using the two systems, the number of problems identified and solved, and time spent on identifying and solving each problem were evaluated. The patterns of using each system to identify and solve problematic features were studied. In addition, the usability of each system was evaluated using a usability survey and interviews. The advantages and limitations of the novice DFM prototype were identified. Since this DFM system was designed for novices, performances of participants with different experience levels were evaluated.

7.2 Methodology

7.2.1 Test Procedures

The benchmark software chosen for the test was DFMXpress, since the workflow is similar to the novice DFM prototype (novice prototype). Both the novice prototype and DFMXpress provide DFM guidelines to users one by one. When using DFMXpress, users need to click the problem one by one to read the feedback. When using the novice prototype, the users need to read slides one by one to read the feedback. Therefore, it is easy to record the time spent on each problem, and make the workflow controlled.

However, there are differences between the DFMXpress and the novice prototype. First, DFMXpress allows users to change manufacturing processes; the novice prototype requires users to use pre-specified machining processes (turning (lathe) and milling). To accommodate this difference, users are told to use these same machining processes at the beginning when testing DFMXpress. Second, DFMXpress can provide feedback to users iteratively after modifying the parts. However, the novice prototype could only provide one round of feedback based on the original parts. To accommodate this difference, the results of using the novice prototype and first round analysis of DFMXpress were compared. The users are required to modify the parts on paper first before doing so in SolidWorks. Figure 28 shows the example paper provided to the participants to modify the parts.

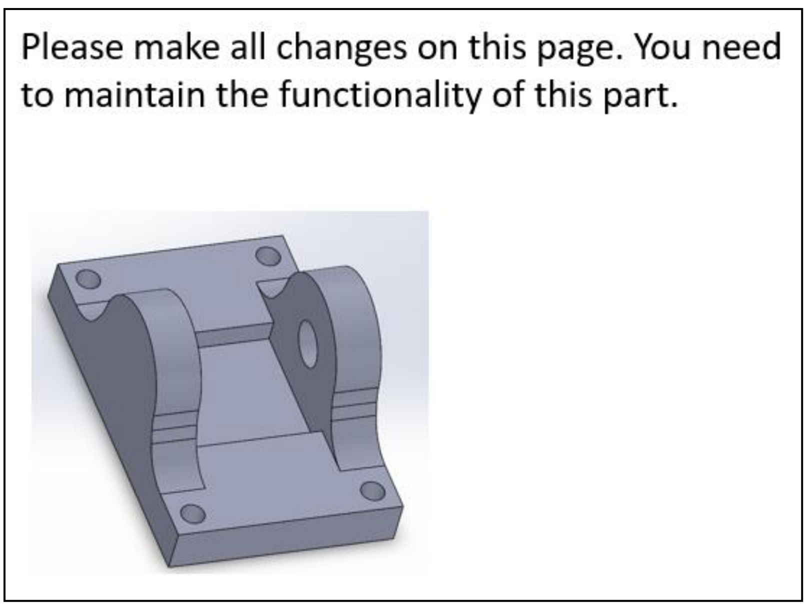


Figure 28 - Example Paper Provided to Modify the Part

The participants were recruited from related classes and posters. They are required to be able to perform basic operations in SolidWorks. The participants were randomly assigned into one of the two groups: 1. modifying given parts using the novice prototype, then using DFMXpress, or 2. modifying given parts using DFMXpress, then using the novice prototype.

At the beginning of the test, the researcher gave the participant the parts and explained the functionality requirements of the given parts. The participant was told to modify the parts based on the feedback provided by the novice prototype/DFMXpress; however, they needed to maintain the functionality of the parts. The participant was asked to modify both parts on paper first. After it was done, the participant was asked to notify the researcher. The researcher then gave the participant the usability survey to gather feedback on using the system to identify and fix the manufacturability problems. Then, the participant was asked to modify the parts in SolidWorks based on the feedback provided by the system they tested. If the participant was using DFMXpress, he/she was allowed to check the parts iteratively after modifying the parts in order to figure out if the problems were solved. When the participant finished modifying the parts in SolidWorks, he/she was given the usability survey again to provide feedback on using the system to modify parts in SolidWorks. Then, this process was repeated for the other system. The participants were asked to modify the same two parts in the other system. When testing the second system, the participant was asked to try his/her best to forget the feedback provided by the previous system. Then, follow-up questions were asked to collect the participant's feedback, comparing the two systems and his/her experience/expertise level in design and manufacturing. The whole testing process was recoded using a camcorder. After the test was done, the video was reviewed to record the time the participant spent to identify and fix each problem. The resolution of the recorded time is 1 second. In order to verify the precision of the measured time, time spent for one problem identification performed by one participant was measured 10 times and averaged, which shows a standard deviation of 0.6 seconds. Informed consent was obtained for all participants, adhering to an IRB approved experimental protocol. Participants were compensated with $10 per hour.

To collect the participants' experience level, the following questions were asked:

1. What is your major?
2. What year are you?
3. What design courses have you taken? Have you designed parts before? If yes, what were the purposes for the parts?
4. What manufacturing courses have you taken? Have you manufactured parts before? If yes, what were the manufacturing processes?
5. Do you have co-op or internship experience related to design or manufacturing?

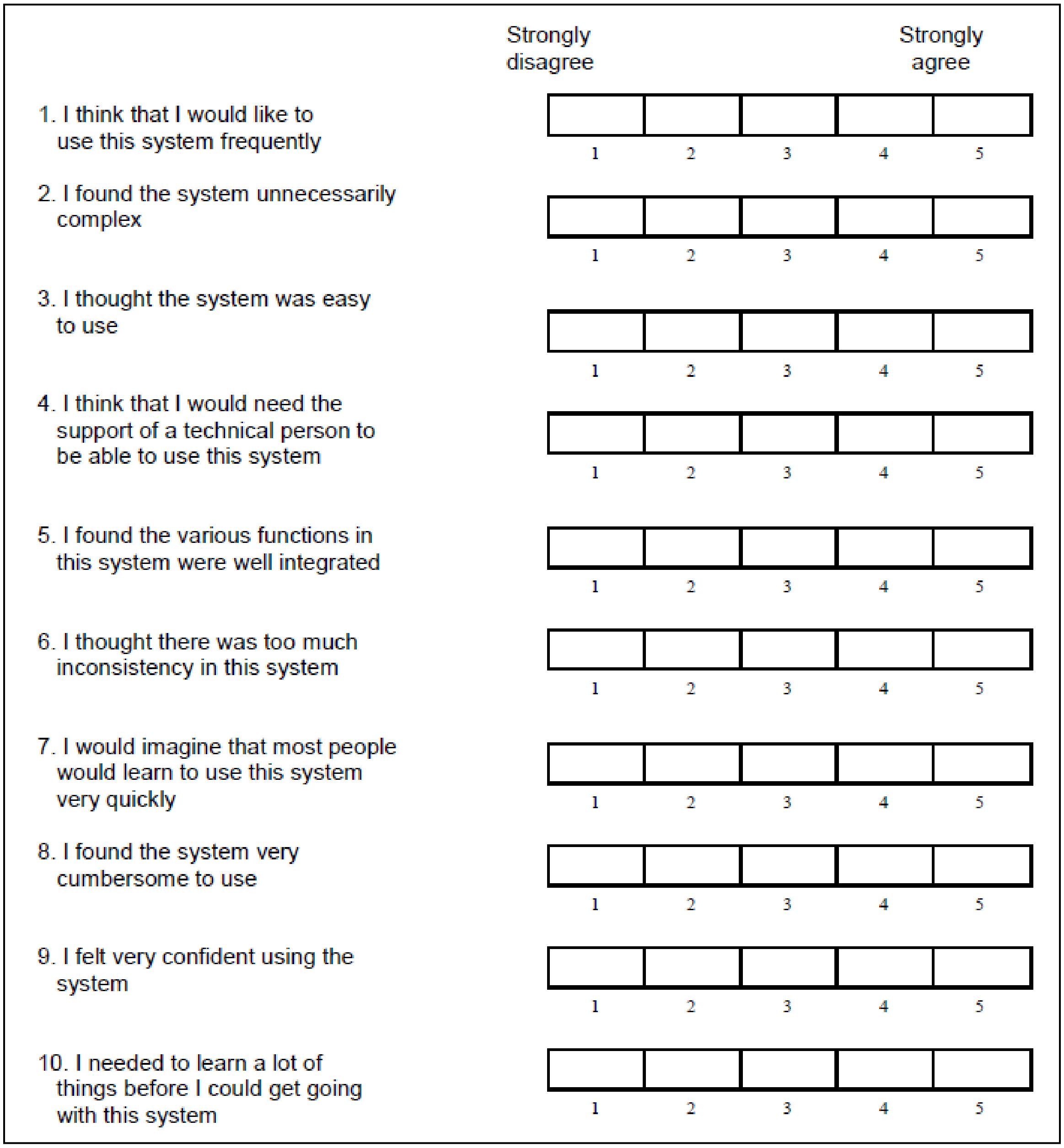
Then, the following questions were asked to collect the participants' feedback comparing the two systems.

1. Comparing the novice DFM prototype and DFMXpress, which one do you prefer to use? Why?
2. If only provided text or only provided pictures, which one do you think will help you identify and fix the problems better? Why?
3. Did you encounter any confusion when using the two systems? (If yes, what were the confusions?)

4. The DFMXpress explains the manufacturing processes; to what extent do you think this information helped you to identify and fix the problems?

7.2.2 System Usability Survey

The usability survey used for this test is the System Usability Scale [192]. It is a fast but reliable tool to measure the usability. It consists of a 10-question survey with five response options for each question. The survey is shown in Figure 29. The ten questions are rated on a Likert Scale from 1 to 5. To calculate the usability score, for each of the odd numbered questions, subtract one from the rated value; for each of the even numbered questions, subtract the value from five. These new values are added up and multiplied by 2.5 to get the usability score out of 100. However, this calculated score is not a percentage.



	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	1	2	3	4	5
2. I found the system unnecessarily complex	1	2	3	4	5
3. I thought the system was easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5. I found the various functions in this system were well integrated	1	2	3	4	5
6. I thought there was too much inconsistency in this system	1	2	3	4	5
7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8. I found the system very cumbersome to use	1	2	3	4	5
9. I felt very confident using the system	1	2	3	4	5
10. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

Figure 29 - System Usability Scale Survey [192]

Studies have been done to convert the usability score to adjective ratings and percentile range. According to Bangor et al., the usability score of 100 represents "best imaginable, above 85.58 represents "excellent", above 72.75 represents "good", and above 52.01 represents "ok" [193]. Based on this work, Lewis and Sauro created a curved grading scale for the SUS [194], which is shown in Table 15. This curved grading scale was used in this study.

Table 15 - Curved Grading Scale for the SUS

Grade	SUS	Percentile Range
A+	84.1-100	96-100
A	80.8-84.0	90-95
A-	78.9-80.7	85-89
B+	77.2-78.8	80-84
B	74.1-77.1	70-79
B-	72.6-74.0	65-69
C+	71.1-72.5	60-64
C	65.0-71.0	41-59
C-	62.7-64.9	35-40
D	51.7-62.6	15-34
F	0-51.6	0-14

In addition to the SUS, four questions were asked to gather participants' feedback:

1. What did you like about the software?
2. What didn't you like about the software?

3. In what circumstances could you see yourself using this software in the future?
4. What was one difficulty you had using the software?

7.2.3 Sample Size Estimation

For this usability test, determining sample size is essential. For comparative studies, Landauer (1988) and Nielsen and Landauer (1993) found that statistically significant findings are unlikely to be produced by a study group of less than eight participants. Therefore, a minimum group size should be eight participants. Macefield (2009) showed that a study utilizing 25 participants per group was quite likely to produce statistically significant findings. Spyridakis and Fisher (1992) found that a study group size of 10-12 participants will often produce statistically significant finding, which also is in accordance with the advice of Rubin (1994) and Faulkner (2003). However, these estimations are general and not based on the settings of the experiment. To estimate the needed sample size for this study, the method development by Sauro and Lewis [195] were used. According to Sauro and Lewis, there are two types of usability studies: summative and formative. The goal of a summative study is to measure the accomplishment of global task goals; the goal of a formative study is to detect and eliminate usability problems. This test is a summative study, since it is aimed to figure out how effectively and efficiently the novice DFM prototype could assist users to identify and fix manufacturability problems.

The method to estimate the sample size is based on a t-test, which assumes normal distribution and with no estimation of variability.

$$e = \frac{d}{s} \quad (12)$$

$$d = e(s) \quad (13)$$

$$n = \frac{z^2 s^2}{d^2} \quad (14)$$

where e is the effect size, s is the standard deviation, and d is the critical difference (i.e., the smallest difference between the observed and true value). Since there are four manufacturability problems with the tested parts, the smallest difference for the percent of problems solved is 25%. Therefore, critical difference d is $0.25\ s$. A confidence difference of 90% is assumed here in order to determine a fairly small effect, so the initial value of z is 1.282. By using Equation 12-14, the initial sample size estimation is 26.3 which rounds up to 27. The results of the first iteration, replacing 1.282 with t for 26 degrees of freedom and 90% confidence (1.315), results in a sample size estimation of 27.7, which rounds up to 28. Thus, the appropriate sample size is somewhere between 27 and 28. The next iteration confirms a final estimate of 28. Therefore, at least 28 participants should be recruited to test the prototype.

7.3 Results

7.3.1 Performance of Participants

Thirty-four participants performed prototype testing. Among these 34 participants, 27 of them were in mechanical engineering, 4 in aerospace engineering, 2 in electrical engineering and 2 in biomedical engineering. Twenty-five participants were undergraduate students, and 9 participants were graduate students.

To measure the participants' performance in using both systems, the number of problems identified, problems fixed, and time spent to identify and fix each problem were analyzed. The summary of the results is shown in Table 16. The standard deviation (STD) and 90% of confidence interval for the results were also calculated. From the results, the novice prototype can assist users to identify the overhang problem in pawn piece more effectively than DFMXpress. For the doorstop piece, the DFM novice prototype and DFMXpress show similar performance.

Comparing the time spent to identify and fix each problem, the novice prototype can assist users more efficiently than DFMXpress in general. The average total time spent on the pawn piece by using DFMXpress was 129 seconds, and by using the novice prototype was 92 seconds. The average total time spent on the doorstop piece by using DFMXpress was 205 seconds, and by using the novice prototype was 166 seconds. For time spent on each problem, the only problem for which the novice prototype did not assist the users more efficiently was the non-standard hole size problem. ANOVA tests were done for comparing the means.

Table 16 - Average Number of Problem and Time Spent to Identify and Fix Problems

		DFMXpress			Prototype			P-Value
		Mean	STD	90% Confidence Interval	Mean	STD	90% Confidence Interval	
Number of Pawn Problem Identified (#)		0.78	0.41	± 0.12	0.97	0.17	± 0.05	0.02
Number of Pawn Problem Fixed (#)		0.70	0.46	± 0.13	0.94	0.24	± 0.06	0.02
Number of Doorstop Problem Identified (#)		2.85	0.44	± 0.12	2.85	0.55	± 0.15	0.06
Number of Doorstop Problem Fixed (#)		2.67	0.72	± 0.21	2.68	0.53	± 0.15	0.09
Time Spent on Pawn (s)	Pawn Problem Identified	54	67	± 19	30	19	± 5	0.047
	Pawn Problem Fixed	75	89	± 28	62	59	± 17	0.051
Time Spent on Doorstop (s)	Non-Standard Hole Identified	16	13	± 4	20	18	± 5	0.35
	Non-Standard Hole Fixed	44	69	± 19	43	77	± 23	0.96
	Inaccessible Feature Identified	36	43	± 12	28	24	± 7	0.36
	Inaccessible Feature Fixed	51	81	± 24	31	32	± 10	0.23
	Sharp Internal Corner Identified	18	17	± 5	8	7	± 2	0.004
	Sharp Internal Corner Fixed	40	55	± 16	36	38	± 11	0.78

Table 17 - Number of Problems Identified vs. Manufacturing Experience

	Number of Participants (#)	Number of Pawn Problem Identified (#)						Number of Doorstop Problem Identified (#)					
		Novice Prototype			DFMXpress			Novice Prototype			DFMXpress		
		Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value
With lathe	25	0.96	± 0.06	0.58	0.72	± 0.15	0.10	2.84	± 0.19	0.73	2.84	± 0.15	0.85
Without lathe	8	1.00	± 0		1.00	± 0		2.88	± 0.19		2.88	± 0.19	
With mill	24	0.96	± 0.07	0.55	0.71	± 0.15	0.07	2.83	± 0.17	0.23	2.83	± 0.16	0.75
Without mill	9	1.00	± 0		1.00	± 0		2.89	± 0.26		2.89	± 0.17	
With both	22	0.95	± 0.07	0.61	0.68	± 0.16	0.12	2.82	± 0.19	0.67	2.82	± 0.17	0.95
With neither	6	1.00	± 0		1.00	± 0		2.83	± 0.25		2.83	± 0.25	

Table 18 - Number of Problems Fixed vs. Manufacturing Experience

	Number of Participants (#)	Number of Pawn Problem Fixed (#)						Number of Doorstop Problem Fixed (#)					
		Novice Prototype			DFMXpress			Novice Prototype			DFMXpress		
		Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value
With lathe	25	0.96	± 0.06	0.58	0.60	± 0.16	0.03	2.72	± 0.17	0.23	2.60	± 0.26	0.72
Without lathe	8	1.00	± 0		1.00	± 0		2.63	± 0.28		2.88	± 0.19	
With mill	24	0.96	± 0.07	0.55	0.58	± 0.17	0.02	2.75	± 0.17	0.36	2.63	± 0.27	0.60
Without mill	9	1.00	± 0		1.00	± 0		2.56	± 0.27		2.78	± 0.23	
With both	22	0.95	± 0.07	0.61	0.55	± 0.17	0.04	2.73	± 0.19	0.38	2.59	± 0.29	0.51
With neither	6	0.96	± 0.06		0.63	± 0.15		2.74	± 0.16		2.63	± 0.25	

Table 19 - Time Spent to Identify Problems vs. Manufacturing Experience

	Number of Participants (#)	Time Spent to Identify Pawn Problem (s)						Time Spent to Identify Doorstop Problem (s)					
		Novice Prototype			DFMXpress			Novice Prototype			DFMXpress		
		Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value
With lathe	25	30	± 7	0.97	55	± 25	0.92	56	± 12	0.87	65	± 18	0.33
Without lathe	8	30	± 7		51	± 13		58	± 20		88	± 36	
With mill	24	28	± 6	0.48	60	± 26	0.68	58	± 13	0.47	63	± 18	0.21
Without mill	9	34	± 11		40	± 12		52	± 16		91	± 32	
With both	22	28	± 7	0.91	59	± 28	0.88	57	± 13	0.67	62	± 20	0.28
With neither	6	30	± 6		57	± 23		57	± 11		65	± 16	

Table 20 - Time Spent to Fix Problems vs. Manufacturing Experience

	Number of Participants (#)	Time Spent to Fix Pawn Problem (s)						Time Spent to Fix Doorstop Problem (s)					
		Novice Prototype			DFMXpress			Novice Prototype			DFMXpress		
		Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value
With lathe	25	67	± 21	0.43	77	± 31	0.84	98	± 33	0.90	114	± 40	0.52
Without lathe	8	47	± 16		69	± 42		103	± 38		155	± 110	
With mill	24	72	± 22	0.12	65	± 17	0.42	104	± 34	0.69	127	± 53	0.93
Without mill	9	36	± 8		95	± 73		88	± 35		122	± 62	
With both	22	71	± 24	0.22	60	± 18	0.94	93	± 35	0.59	99	± 38	0.76
With neither	6	68	± 20		80	± 29		107	± 32		137	± 51	

Table 21 - Number of Problems Identified vs. Design Experience Type

	Number of Participants (#)	Number of Problem Identified (#)					
		Novice Prototype			DFMXpress		
		Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value
With Class	26	3.77	± 0.16	0.80	3.54	± 0.20	0.07
Without Class	7	3.71	± 0.28		4.00	± 0	
With Project	19	3.63	± 0.22	0.09	3.63	± 0.22	0.96
Without Project	14	3.93	± 0.11		3.64	± 0.27	
With Research	10	3.70	± 0.33	0.24	3.60	0.35	0.40
Without Research	23	3.78	± 0.14		3.65	± 0.19	
With Intern	9	3.56	± 0.38	0.16	3.67	± 0.37	0.86
Without Intern	24	3.83	± 0.13		3.63	± 0.19	

Table 22 - Number of Problems Fixed vs. Design Experience Type

	Number of Participants (#)	Number of Problem Fixed (#)					
		Novice Prototype			DFMXpress		
		Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value
With Class	26	3.69	± 0.17	0.61	3.31	± 0.29	0.50
Without Class	7	3.57	± 0.31		3.57	± 0.45	
With Project	19	3.53	± 0.22	0.08	3.21	± 0.38	0.26
Without Project	14	3.86	± 0.15		3.57	± 0.27	
With Research	10	3.60	± 0.35	0.25	3.50	± 0.35	0.88
Without Research	23	3.70	± 0.16		3.30	± 0.33	
With Intern	9	3.56	± 0.38	0.48	3.33	± 0.45	0.91
Without Intern	24	3.71	± 0.15		3.38	± 0.30	

Table 23 - Time Spent to Identify Problems vs. Design Experience Type

	Number of Participants (#)	Time Spent to Identify Problem (s)					
		Novice Prototype			DFMXpress		
		Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value
With Class	26	84	± 14	0.74	120	± 36	0.64
Without Class	7	91	± 29		142	± 44	
With Project	19	85	± 18	0.93	103	± 23	0.15
Without Project	14	86	± 18		158	± 63	
With Research	10	87	± 23	0.90	105	± 19	0.48
Without Research	23	85	± 16		134	± 42	
With Intern	9	79	± 15	0.62	73	± 21	0.09
Without Intern	24	88	± 17		145	± 39	

Table 24 - Time Spent to Fix Problems vs. Design Experience Type

	Number of Participants (#)	Time Spent to Fix Problem (s)					
		Novice Prototype			DFMXpress		
		Mean	90% Confidence Interval	P-Value	Mean	90% Confidence Interval	P-Value
With Class	26	171	± 49	0.60	199	± 61	0.80
Without Class	7	131	± 55		225	± 160	
With Project	19	130	± 32	0.22	151	± 47	0.15
Without Project	14	199	± 80		274	± 116	
With Research	10	175	± 50	0.80	246	± 123	0.56
Without Research	23	159	± 55		189	± 66	
With Intern	9	221	± 137	0.28	79	± 20	0.06
Without Intern	24	147	± 29		254	± 76	

The performances of participants with different experience levels were also evaluated. Two categories of experience were studied: the manufacturing experience and design experience in class, research, personal projects and internships.

For the manufacturing experiences, the participants experienced in milling and turning were studied since the pawn piece should be made using a turning process and the doorstop piece should be made using a milling process. The manufacturing experiences were classified into seven categories: with lathe experience, without lathe experience, with mill experience, without mill experience, with experience in both processes, with experience in either process and with experience in neither process.

Table 17 shows the average number of problems identified and Table 18 shows the average number of problems fixed by participants with different manufacturing experiences. For the pawn piece, the results show that participants without lathe experience could identify and fix the overhang feature problem more effectively than participants with lathe experience using both systems. For the doorstop piece, the results show that participants with mill experience could identify problems more effectively than participant without mill experience. In addition, participants with no experience with the lathe and mill could identify the problems more effectively than participants with experience in both lathe and mill. In general, users without experiences in the related manufacturing processes can identify the problems more effectively than users with experiences.

Table 19 shows the average time spent on identifying and Table 20 shows the average time spent on fixing the problems by participants with different manufacturing experiences. From the results, participants with experiences could identify problems faster than participants without experience; however, they did not always fix the problems faster.

Table 21 shows the number of problems identified and Table 22 shows the number of problems fixed by participants with different design experiences. When using the novice prototype, participants who have taken design classes performed better than participants who had not taken design classes. However, participants without experience in personal projects, research or internships performed better than those with the experiences. When using the DFMXpress, participants without experiences also tended to perform better than participants with experiences. In addition, Table 23 shows the time spent on identifying problems and Table 24 shows the time spent on fixing problems by participants with different design experiences. The novice prototype could assist users without experiences to fix problems more efficiently; however, it did not assist users without experiences to identify problems faster. DFMXpress could not assist users without experience to identify and fix problems more efficiently.

Therefore, participants without experience in manufacturing or design tend to perform better than participants with experience. One possible explanation is the experience measured in the current study did not represent the DFM expertise level. The skills in design for manufacturing cannot be learnt from design activities or manufacturing activities. Another potential explanation from the literature is that designers with more experience tend to consider more alternative solutions; however, they also are easier to become fixated on one specific solution. When designers become fixated on one solution, they tend to not to follow the suggestions given by the feedback system.

7.3.2 *Usability Results*

For the usability survey, 33 participants completed the survey for the novice prototype, and 30 participants completed the survey for DFMXpress. The usability scales for using each system to identify problems and then mark changes on paper, and modify the parts in SolidWorks were calculated and converted into percentiles and letter grades using the curved grading scale shown in Table 15. The summary of the usability results is shown in Table 25.

Table 25 - Summary of Usability Survey Results

	SUS		Percentile	Grade
	Mean	STD		
Novice on Paper	71.21	16.49	60.32	C+
DFMXpress on Paper	72.17	18.39	63.05	C+
Novice in SolidWorks	77.31	15.89	80.27	B+
DFMXpress in SolidWorks	71.25	19.49	60.43	C+

Comparing the usability of using the novice prototype and DFMXpress to identify and fix problems on paper, both systems got C+. The percentile score of DFMXpress is higher than the novice prototype. In order to determine which features increase and decrease the usability of each system, the feedback from the participants was investigated. For the novice prototype, 11 participants answered that visualization with example pictures was what they liked about the system. Twenty participants answered that input tolerance was what they did not like about the system. For the DFMXpress, 7 participants answered that clicking one button to show the feedback quickly was what they like about the system. Eleven participants answered that lack of understanding of the terminology was what they did not like about the system.

Comparing the usability of both systems to modify parts in SolidWorks, the novice prototype got a higher average score than the DFMXpress. An ANOVA test was performed, resulting in p-value of 0.20, which shows that the means are not statistically significantly different. A potential explanation for the higher average score could be that when using the novice prototype to modify parts in SolidWorks, the participants only needed to apply the changes. Therefore, when they were rating the usability, they actually rated the usability of SolidWorks primarily. Since SolidWorks is a well-developed CAD software, it should receive a higher score. When the participants were using the DFMXpress to modify the parts, they were allowed to check the part whenever they made changes if they wanted to make sure they fixed the problems. During this process, if the participants already identified the problem but did not know how to fix it, the participants may have felt frustrated after many unsuccessful attempts, which could decrease the usability of DFMXpress.

7.4 Discussion

7.4.1 Example Parts

Visualizations with example parts should be able to assist novice designers better than only text. When the participants were asked to compare only text and only pictures, 19 out of 29 participants said only pictures could better assist them to modify the parts, since the pictures are more straightforward.

From the results, the novice prototype could not assist the designers to identify and fix the non-standard hole size faster than using DFMXpress. For the doorstop piece the participants needed to modify, the hole size is 5.13 mm. Regarding this problem, DFMXpress provided instruction that “the nearest standard hole size is 5.1 mm and 5.2mm.” From the pilot study, the participants were asked to compare using this text as guideline or a standard drill size table. The participants chose the text provided by DFMXpress, since it is more applicable to this case. Therefore, this text was used for the formal testing. The novice prototype also provided the picture shown in Figure 30 for visualization. This picture only shows different numbers for the hole size that .187238 is “bad”, and .20 is “good”, which is not directly applicable to the doorstop piece. Therefore, the designers did not acquire additional information from the visualization, but did spent more time to read the feedback.

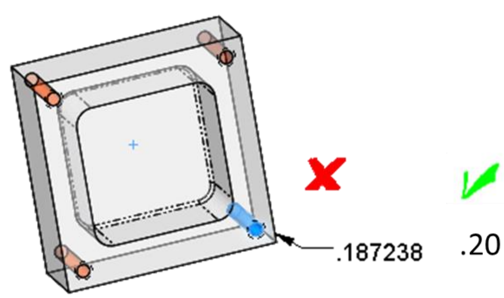


Figure 30 - Example Part for Non-Standard Hole Size

In addition, some participants could not understand the example parts provided for the inaccessible feature problem. Therefore, another set of example parts were provided to the participants later. The two sets of pictures are shown in Figure 31. Among the 34 sets of tests, 17 sets of tests only used the original example parts as feedback, and the other 17 sets of tests used both sets of parts as feedback.

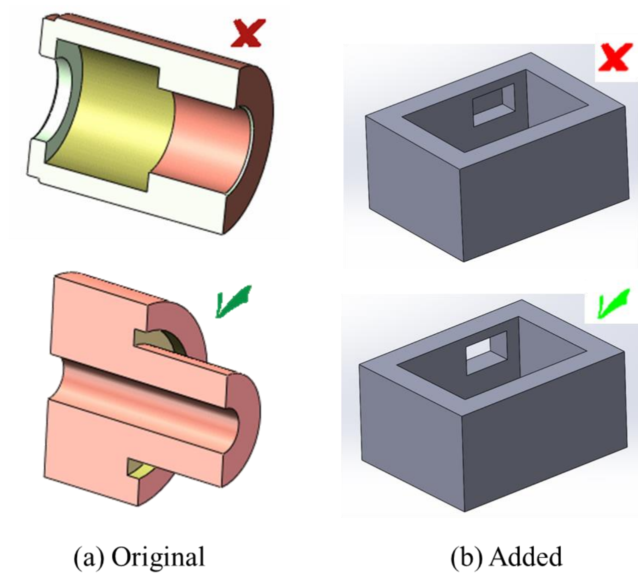


Figure 31 - Two Sets of Example Part for Inaccessible Features

For doorstop piece, the average number of problems identified increased from 2.69 to 2.88, and the average number of problems fixed increased from 2.56 to 2.83 after adding the second set of example pictures. The average time spent to identify the inaccessible feature problem decreased from 40 s to 16 s. The average time spent to fix the problem decreased from 43 s to 21 s. When only using the first set of example pictures, four out of 17 participants could not fix the inaccessible feature problem. When using both sets of pictures, all participants could identify and fix the inaccessible feature problem.

After the new set of pictures was added, the participants were asked to identify which set of pictures could better assist them to identify and fix the problems. Fourteen participants said the new one, two said the old one, and one said both worked the same. The participants that preferred the new set of example parts said, “they are similar to the doorstop piece” or, “they are more applicable to this case”. The participants that preferred the original set of example parts expressed that it showed more detailed information than the new set.

Since the main purpose of this testing is to compare the participants' performance using the novice DFM prototype and DFMXpress, changing the example pictures during the tests could impact the comparison results. From the results shown in Table 16, the average number of problems identified was 2.85, fixed was 2.68 using the novice prototype; the average number of problems identified was 2.85, fixed was 2.67 using the DFMXpress. Participants spent less time to identify and fix the inaccessible feature problem using the novice prototype than using the DFMXpress, even with including the data generated using just the first set of example pictures. Therefore, the novice prototype may not necessarily increase the number of problems identified or fixed, but could increase the efficiency of identification and fixing of problems, when compared to DFMXpress. The change of pictures did not influence this conclusion. In addition, looking at a confusing picture could be frustrating and influence the subsequent design performance. The problem after the inaccessible feature problem was the sharp internal corner problem. After adding the second set of example pictures for inaccessible feature, the time spent to identify the sharp internal corner problem decreased from 10 s to 7 s, and the problem fixing time decreased from 45 s to 28 s. This decreasing trend was not observed for the non-standard hole problem, which was presented to the participants before the inaccessible feature problem. Therefore, providing confusing pictures could decrease the performance of designers on other later tasks, beyond that including the confusing pictures.

From these two cases, information provided more applicable to the designed parts could better assist the novice designers to identify and fix the manufacturability problems. If the visualization with example parts could not provide additional information to the designers, it could increase the time the designers spent.

7.4.2 Limitations of the Novice DFM Prototype

The limitations of the novice DFM prototype stem from the limited functionality. The current prototype could not automatically analyze and provide feedback. Therefore, it could not provide synchronous feedback to novice designers. To construct an automated system, an automated geometric recognition and analysis method that recognizes parts' features and geometries is required. In addition, the tolerance input is a major issue. From the interviews and observations, the machinists identified the tolerance as an important factor to determine the failure risk of the parts. When the user did not know how to determine the tolerance values, the machinists could help them by using their experience and expertise. The novice prototype only provides the suggested value for the overall tolerance, but does not provide recommendations for critical parts like the machinists can. Therefore, the novice designers are not able to determine the specific tolerance values due to the lack of knowledge. In order to increase the usability of the novice DFM system, an automatic tolerance suggestion function should be implemented.

In addition, the current novice DFM prototype cannot provide feedback on manufacturing costs of the parts. In addition, an effective strategy to provide the manufacturing cost was not able to be identified from the observations, since the machine shop does not charge for labor. Without the manufacturing cost feedback, the designers cannot evaluate their designed parts from monetary and sustainable perspectives. A manufacturing energy consumption estimation framework using a machine learning approach was developed by the author and the co-authors [66]. To improve the usability of the novice DFM prototype, this framework should be implemented.

7.5 Summary

This chapter shows the testing results of the developed prototype. Based on the testing results, the novice DFM prototype can assist novice designers better than the benchmarking software DFMXpress. For the pawn piece used for the testing, the novice prototype could assist the participants to identify 0.97 ± 0.05 problems, and fix 0.94 ± 0.06 problems. When using the benchmarking software, the participants only identified 0.78 ± 0.12 problems, and fixed 0.70 ± 0.13 problems. In addition, the novice prototype can assist designers without experience in manufacturing and design better than assisting designers with experience. One possible explanation is the experience measured in the current study did not represent the DFM expertise level. The skills in design for manufacturing cannot be learnt from design activities or manufacturing activities. Another possible explanation for this result is that more experienced designers tend be become fixated on one design solution.

From the testing, visualization with example parts could assist the designer to better modify the parts compared to only providing text. In addition, information that is more applicable to the designed parts tend to assist the designers to identify and fix the manufacturability problems better. If the visualization with example parts does not provide additional information to the designers, it could increase the time the designers spend.

In addition, the limitations of the current prototype are identified. Future work should be done to improve the prototype. The future work needed is discussed in Chapter 8.

CHAPTER 8. CONCLUSIONS

8.1 Overview

For additive manufacturing, such as FDM used by novice designers, the baseline waste rate for material consumption was 35-45% which increased the energy usage by 45%. This result motivated the development of a guidance system to assist the novices to decrease their fabrication failures. Based on these motivating factors, this dissertation addresses these opportunities through the design and development of such a system.

The feedback content and strategy for the software system were identified based on the research findings in this dissertation. Using the identified feedback content and strategies, a novice DFM prototype was developed and tested. Comparing the mean values, the novice prototype could assist participants to identify and fix more problems in shorter time than DFMXpress. From statistically significant results, the novice prototype could assist the participants to identify and fix more problems than DFMXpress for the pawn piece since the visualization using example parts could assist the novices to make better design decisions. For the pawn piece used for the testing, the novice prototype could assist the participants to identify 0.97 ± 0.05 problems, and fix 0.94 ± 0.06 problems. When using the benchmarking software, the participants only identified 0.78 ± 0.12 problems, and fixed 0.70 ± 0.13 problems.

8.2 Contributions

The first contribution of this work is showing that experience is different from expertise. From literature, expertise is primarily a result of experience [49,50]. Therefore, researchers tend to measure an individual's experience in activities to quantify the level of individual's expertise. However, experience level can indicate expertise, but cannot directly measure the experience from these results of this study.

The studies of the FDM failure causes and the prototype testing both evaluated participants' experience levels in design and manufacturing. However, very few statistically significant results were found from these two studies. In addition, participants with experience tend to perform better than participants without experience for the prototype testing. One possible explanation is the experience measured in the current study did not represent the DFM expertise level. According to Gelder, the skills in a specific domain cannot be learnt from studying other subjects, it must be studied and practiced in its own way [142]. Therefore, the skills in design for manufacturing cannot be learnt from design activities or manufacturing activities. Individuals should put deliberate effort in practicing design for manufacturing activities. Deliberate practice is the primary mechanism to create expert-level performance in a domain is deliberate practice [49], which is a special type of experience. According to Ericsson and Charness, individuals cannot improve their performance and reach an expert level through automatic consequence of more experience with an activity, but through deliberate practice [141]. Deliberate practice is an effortful activity motivated by the goal of improving performance. There are four characteristics of deliberate practice [141,142]:

1. It is done with full concentration aiming at generating improvement;
2. It is engaging in the skill itself and doing special exercises designed to improve performance in the skill;

3. It is graduated. Easier activities are mastered through repetition before harder ones are practiced. And the practiced activities become harder gradually;
4. It is done with close guidance and timely, accurate feedback on performance from experts.

Therefore, future work should be done to measure the DFM expertise level of individuals, and investigate its relationship with fabrication failure rates.

The second contribution of this work is the identification of effective feedback content and strategies for machining from observations and interviews of machinists and designers. To identify the effective feedback content and strategies, communication failures were identified for machining. Previous studies of machining fabrication failures focused on the machine itself [70], but did not consider the failures caused by human factors.

The feedback content identified includes the DFM guidelines and design suggestions to inform novice designers about how to make changes to fix problems with their designs. The feedback strategies identified include visualization of problematic features by highlighting the features and providing example pictures to show high manufacturability and low manufacturability features. Highlighting problematic features is the strategy adopted by both benchmarking software DFMXpress and the novice prototype. It also mimics the experts' actions during the face-to-face communications. From the survey results, it is an effective strategy to assist the novices to identify the problematic features. Providing example pictures to show high and low manufacturability features is an effective strategy to assist the novices to fix the problematic features. These identified feedback content and strategies will be adopted to develop an automated DFM software tool to assist designers make design decisions with minimized fabrication failure risks. This automated DFM software tool will be a fundamental part for the overall CAD-CAM software system.

8.3 Limitations

First, the novice engineering designers in this work are designers at the early stage of mechanical design training. The novices include, but are not limited to, students. The novices also include inexperienced practitioners in industry. However, the studies in this work were primarily focused on students. The experiments, observations and interviews were conducted within a university. Therefore, some concerns of mechanical design could be overlooked, such as the monetary cost of making parts. In order to collect more comprehensive data, studies should also be done in commercial machine shops.

Second, the design of experiments did not effectively measure the expertise level of participants. For the studies, experience in design and manufacturing were measured separately in order to evaluate the individual's expertise level in DFM. However, it did not work as expected. Therefore, future works should be done to accurately evaluate the DFM expertise level of each participant. To evaluate the participants' DFM expertise level, questionnaires with knowledge questions for design, manufacturing and DFM will be used.

8.4 Future Work

The participants using the novice prototype tend the perform better than using DFMXpress due to two reasons from the survey feedback: the minimized usage of terminologies in text and the visualization of possible solutions using example parts. Future tests should be done to evaluate the quality of text and visualization used to provide feedback. For the quality of text, future test will be done to ask the participants to identify and fix problems using statements with terminologies and statements with minimized terminologies. The results including numbers of problems identified and fixed will be compared to test the hypothesis that novice designers could perform better using guidelines with minimized usage of terminologies.

For the quality of visualizations, the revised hypothesis is information provided more applicable to the designed parts could better assist the novice designers to identify and fix the manufacturability problems. When novices approach problems, they base on the literal features of the problems; however, the experts use principles to solve a problem representation [196]. To test the revised hypothesis, sorting activities should be done by providing different representations and example pictures for manufacturability problems to participants at different expertise levels. The participants will be asked to select the example pictures which they think could best assist them to fix the problems. The identified high-quality visualization will be implemented into the DFM software tool to provide most effective visualization assistance to designers.

With the high-quality text and visualization identified, future test should be done to evaluate if providing only text, only visualizations of example parts, or both could assist the designers more effectively and efficiently. It is expected that providing both information can assist the designers better. However, it could also increase the time spent to identify and fix the problems. Therefore, future tests will be done to by asking the participants to modify parts using only text, only visualizations, and both. The best approach identified will be implemented into the DFM software tool.

In addition, the novice prototype did not show statistically significantly differences from the DFMXpress in usability results. There are two weak points of the novice prototype from the survey feedback. First, the tolerance recommendation function was not fully developed. Second, the novice prototype was not integrated into SolidWorks. Therefore, users could not get feedback from clicking one button to show feedback quickly. Therefore, the novice prototype is expected to be more usable by providing recommended tolerance values for parts automatically, and integrating into SolidWorks. After implementing these two functions, the usability scores of the novice prototype and DFMXpress will be compared to show if the prototype is more usable than the benchmarking software.

Moreover, from the results of the prototype testing, the novice prototype was able to assist designers without experience in manufacturing and design better than it was able to assist designers with experience. One possible explanation is that the experience measured in the current study cannot represent the expertise level of the individuals. Another hypothesis is that more experienced designers tend be become fixated on one design solution. Therefore, future test should be done to ask the participants to modify parts without interventions first, and then modify the same parts again with guidance provided. Results will be compared to see how people with different expertise level performed in order to test the hypothesis.

In addition, the findings from the studies of FDM and CNC machining should be integrated to develop a feedback system for both AM and SM processes. The environmental impacts of CNC machining in a novice environment should be investigated. The framework developed in Chapter 3 for estimating the environmental impacts of FDM should be applied to CNC machining with minor adjustments in the operating phases considered for energy consumption and failures modes. The failure sorting instructions should also be modified for the CNC machining process. In addition, the current novice DFM prototype only applied to the CNC machining process. This prototype should be expanded to support AM. The failure types of FDM have been identified in Chapters 3 and 4. These findings should be implemented into the developed algorithm to support feedback for FDM. With the integration of feedback systems for both AM and SM processes, the system should also be applied to hybrid manufacturing processes.

An automated DFM guidance software tool will be constructed from the findings of these future studies, and become a fundamental part for the overall automatic CAD-CAM system that enable individuals at different expertise level to engage in product design and production. It will increase the opportunities for innovations without increasing the environmental impacts.

APPENDIX A. QUOTES FROM OBSERVATIONS AND INTERVIEWS

A.1 Observation Quotes

M: Machinist

D: Designer

A.1.1 Job submission and pick-up process

Observation 1:

- M: Did you put the request? (The machinist opened the request website.) When I get it done, you will get an email. I will put it on the shelf. The shelf on the left is the incoming shelf. The shelf on the right is you can come and pick up the part.

Observation 3:

- M: So you guys did not submit a job request. This is important. We start to prioritize the capstone project.
- M: You should go to the me machine shop website, click here, submit the request. Make sure you put senior design, then we know it. As long as you put it here, we will probably prioritize all capstone this week.
- M: Do you have the SW for this file? Can you send them to the machine shop email? Because you never submitted a CAD, you only submitted the drawing. We need the SW.

Observation 4:

- M: Put your name on it, and put it on the shelf on the left. The shelf on the left is incoming drop-off; the shelf on the right is for pick up.

Observation 5:

- M: If you go to the MMM website. This is our list of jobs. Please specify your name, your contact info, material, specify that you are for capstone design. For there, it gives you space for SW drawings, the more info we have the better. Put on your name on the material. If we have any question, we will email you. I don't want this (paper drawing).

Observation 7:

- M: So all the other thing, mmm webpage, you go there, you will see something about the technical request. You do that, that put you in the queue. When we have it done, we can send you email. Then you can pick it up. We will do this, fill this out, there is a place there to add your SW drawings. Please send me your electronic file. As much information, the more information you will help out. The least information that I will say come on. Any electronic file, hard copy is good, drawings files, part files, assembly files, everything.

Observation 8:

- M: So if you go to our website. (The machinist showed the machine mall website.) You go here, machine shop technical request, and fill out the information, your name, your grad or undergrads, whatever you are. Leave your contact information here. Research, material, department, affiliation. Here is your drawing, we make your drawing. You can also supply your drawing. Fill the information you have, submit this form. When we have it done, we will email you. You need to leave everything with me. And you can leave this with me. That is all I need (material, sketch, supply bar).

Observation 11:

- M: I like you to do to go back on our website, submit the request again. Just fill out the request, and say you are trying to reposition the pieces of the chain. And that's all.
- M: If you can do that (submit the form again), it will give me some kind of documentations. Submit the request, just put the rework.

Observation 13:

- M: Give me a technical request, you want to cut it.

Observation 14:

- M: Submit your SolidWorks, your pdf, everything.

Observation 15:

- M: We need CAD model and more information.

Observation 16:

- M: Something else, you gave me the SolidWorks. You need to give me the part file. I cannot open the drawing file without the part file. I also need the assembly. What I need is that you send me the assembly file, the part file. And we will review it. If everything goes right, we are going to have… three assemblies in total, and six parts for each.

A.1.2 Part features/dimensions clarification

Observation 1:

- When we talk about features. What features are required? What features are more for aesthetic purpose? Clearly, you need these laps. These are for?

Observation 2:

- M: These features are important? Could they just be round? Does it need to be? What does this cut-out for?

Observation 5:

- M: What does the .65 inches for?

Observation 6:

- M: Let me take a look at your drawing, I did see you email. (The designer explained the drawing, just cut it into half, explaining by pointing to the piece of material.)

Observation 7:

- M: Now this, is this one two pieces or one pieces?

  D: This need to be perpendicular, I don't know how to.

  M: What we probably do is to put a small center on here. We will take it to the machine, will machine this out.

D: So one piece is better?

M: I don’t know, we can try, we can press it in.

Observation 8:

- M: Okay, 3” by 3”. And you want to cut it in half. Cut in half, and drill M8.
- M: It has thread. Do you want to do it on one half or both half?

Observation 11:

- M: What is the position of this part you want?

  D: As close to the bottom of this chain as possible.

  M: So it will be all the way up.

Observation 12:

- M: I would like to find out the space in between each one. This one got .11, is that the space?

  D: this one will look like this. (The designer draw on the drawing.)

Observation 13:

- M: It needs to be 45 or 60 degrees? Just one angle, or you want a lot along the side?

  D: Cut it to half. How to measure the angle?

  M: We can use the optical comparator. Let me show you. The optical comparator is very good for the angle. (The machinist showed the designer how to use the machine.) What we will do is you want to sketch it? Or you just cut it down? (The machinist marked and wrote on the block using to mark how to cut.)

Observation 14:

- M: What is the width and depth?
- D: 1 mm by 1mm.

Observation 16:

- M: You have an assembly drawing here. We can look at it. I am not sure how long is your rod that's gonna be in it.

  D: it will be about half an inch.

A1.3 Material

Observation 3:

- M: Did you guys decide what kind of material is best for the hinge?

  D: Nylon.

Observation 5:

- M: What we will do is now the material for this is 1080 steel right?

  D: Yes.

Observation 6:

- M: So I mean is this really soft or glassy? When you say glassy carbon.

  D: It is not soft.

Observation 7:

- M: This material is what?

  D: Plastic, anything is easy. Delrin is a little expensive, that is what we like, good quality, good manufacturability.

- M: You will need to order material. (The students do not know what material.) Let's look at it.
- This is the steel? Is it stainless steel?

  D: Yes.

  M: Does it make different to what type of stainless steel? We prefer 303, which is easy to machine stainless steel. I don't like 316, but it's used a lot in the aerospace, combustion lab, a lot of heat, the easy thing the better. Half inch is the thick about this.

  D: That has to be Teflon.

  M: The easiest thing is you order your material. I don't charge anything for the time. there is nothing for our machine time. if we need to buy some glue, we will charge that. Teflon, obviously a round piece of Teflon.

  D: It is good that you tell us what to buy.

  M: I will say round piece of Teflon, McMaster-Carr. Give us at least 3 inches (of material). It usually comes in 1, 3, 6, 12. This one we have to machine. This is 4 inches Delrin. I am sorry, it is a little bigger, 4 and half. The height… 1.35. we probably 6 inches of this.
- M: What about bearing? Are you going to order bearings? You will do this in standard piece?

  D: Yes.

  M: Is it gonna be an oilite bronze or just regular bronze? What type of material is this?

  D: Whatever Mc-Master has. what do you recommend?

M: It depends can you use the oilite? It is actually embedded with oil. It is going to lubricate your shaft.

- (They are looking at McMaster-Carr, showing pages with bronze bushings.)

  M: You may want to buy something like this. Oil-embedded, we call it oilite, then you can see here.

  D: Yes, it might be better than what we have.

- D: can you remind me what is for the steel rod?

  M: 316, I don't like 316, telling you that, but it is more corrosion resistance, better.

  D: Aluminum won't be strong enough?

  M: It may be strong enough. Let me see here, some good quality, 7075 aluminum, 400 may be okay. Let me see here. Is it magnetic? You don't care. 303 is the one. It is really close to 304. If you look into the characteristic, you may find 304 works. 316 is the superior for the corrosion resistance as I told you. I hate to tell you that because (the manufacturability). Aluminum maybe okay. What is your RPM? What about your forces? Let's look at that. A good quality 7078, for the corrosion resistance, we go to the 2000 series.

  D: You want me to get aluminum.

  M: Yes, I like aluminum.

  D: Let's get 2024.

  M:Just give me a piece, let me turn it down. We may come back to 316.

Observation 8:

- M: The material is MACOR.

Observation 12:

- M: What is the material? Aluminum?
- D: yes.

Observation 13:

- M: It is acrylic.

Observation 14:

- M: What is the material?

  D: Only braze copper.

  M: Copper is soft, really gummy, really hard to machine.
- M: You might need to look at oxygen-free copper. It is good for braze.

Observation 15:

- M: What we would probably have to do is to get a piece of MACOR. The problem of the MACOOR is the price and the machinability. My concern is that we need to find out the hardware.

Observation 16:

- M: Everything is made of stainless steel.

A.1.4 Lead time

Observation 1:

- D: What is your estimation of the lead time?

M: It is probably about two weeks and half. It depends on the availability of the EDM. We might get it towards the end of next week.

Observation 2:

- M: When is your competition?
- M: This came in last year, but too late. This year you come early.

Observation 3:

- M: We have two weeks left (to thanksgiving). So you have four weeks left. There are only 20 working days left.

Observation 4:

- M: It will be probably about a week and half.

Observation 7:

- D: What is the turn around time for us?

  M: We got about a week turn-around time. but capstone is coming up. you know capstone. So reality is … the most is about two weeks.

Observation 10:

- M: We are now a week and half behind. It is probably sometimes next week. Is it okay?

  D: Yes.

Observation 11:

- M: It probably will be Monday or Tuesday.

Observation 13:

- M: It may be done tomorrow.

Observation 14:

- M: We are in capstone, so we will be around two weeks back.

A.1.5 Explaining manufacturing processes

Observation 1:

- M: We will do is to cut the shape. The only thing I will do is to put a straight line along this. Then I will do is coming in and coming out.

Observation 2:

- M: Currently, your machining process will be you take a piece and machine it out, turn this. And rotate it, and turn this, then you still got a big section in the middle, right? You need to fixture it, then you have a really long tool coming down and machine it.
- M: So with a fourth axis, the machine will actually rotate. if we're gonna machine the part as designed, you know having a fourth axis would be ideal. Cause we could clamp here and machine this, rotate and machine this, rotate, machine this. You could even do almost all of this. This is turning, this is turning. For me, this is kind of a big challenge. Because this is too deep.
- M: If you have a way, this part could be wire EDM. If you can go all the way through.

- M: I am going back to vertically doing this, and set it horizontally doing this. You know machining all this, machining this, you going as far as you can, and then rotating. That is kind of where I think it is a good way to do this part.

Observation 4:

- M: I've got an idea. What I am gonna do is to machine it. We are going to probably cut it off with aluminum material, and you said the thickness does not really matter. We may cut to that thickness, and put it back to the lathe, and machine it again, push it up again to machine it again. So the faces are parallel. So it will be machined surfaces. Not ground, it will be machined, it will be mirrored, like this (with example for machined surface).

Observation 7:

- (The students ask the feature (groove), hard to machine)

  M: Because you are doing on milling machine, you cannot do it on a lathe. Is it like a o-ring groove?

  (Student talk about design change, say do not know how to draw on drawings.)

  M: What we can do is using a 1060 end-mill. Let's change this to 1/16, that will give us the ability 2000. Half mm, no problem (checking drawings).

Observation 9:

- M: You know a file. And what we want to do is just to use the file to make the gap a little bigger. When you use the file, you can even use stroke to clean this face to keep it straight. We will do that. Whatever you do, you want to make sure the file is parallel to the surface.

- M: And do this side, turn it around. And remember file only do cuts in one direction. See how it has slots, only cuts in one direction. Only cuts so you can file it.

Observation 14:

- M: All we do is cut that plate, give a hand on the plate, glue the pieces. If you bring it back, we will wire EDM it.

Observation 16:

- M: The threaded will be welding. The round will be threaded, and we will go a little bit deeper to 100 thousandths.

A.1.6 Assembly/Mating pieces

Observation 2:

- M: Would you come to a mate part that cannot be changed? (

  D: Connected to a tripod.

  M: Where is the tripod is come from, from the car itself or it is something you made by yourself? If you control the mating piece of this, could you perhaps change. So it is much larger radius give you much large tool. So the mating piece is changed to where it has different configurations. So this small corner radius you can come with large tool because you have large radius which in terms of stronger because of larger radius.
- M: If there is something else go on there?

  D: Yes.

Observation 8:

- M: It mates by? You probably want to leave that with me (the rod the part will mate to)? Can you leave it with me.
- M: You want it thread just this depth?

  D: I want more.

  M: You cannot go any further of this any way. Fit supply bar. Once it hit there, it is gonna stop anyway. Because this diameter is small than this diameter. Cause your bar is gonna like this (sketching the assembly view), it can only go so far. I can go this deep, but it can only go this bit. Because it is gonna hit this shoulder.

  D: This is going to be in high temperature, so want it to be deeper.

  M: Yes, we can make it. So that will be deeper.

Observation 10:

- M: Did something fit inside here? Is something fit here? Is something inside the hole?

  D: Battery.

  M: So that's not a problem. So what about the other?

  D: it fits a spring inside.

  (Machinist checked the dimension)

  M: What is the size of your spring?

  D: I don't know right now.

Observation 15:

- M: There are screws here. If it needs to go all through this and this hardware, that is what we need to concern.

  D: This will be connected to wires. So it does not need to be long.

  M: The first thing we need to do is to figure out the size of the fasteners.

Observation 16:

- M: So it has to be remote, right?

  D: the reason we are going to do that is because we got a ceramic plate that has a hole in it. That plate will go from the bottom and then gripped from the top.

A.1.7 Process/Machine/Tool Selection

Observation 2:

- M: Go look at Multus (multitasking machine), or you can mill-turn. Take a look at that process and see how it can be applied to this part. Or just the fourth axis on a mill, which can make it rotate like this. Take a look at it from a programmer perspective.

Observation 6:

- I will need to do is to investigate to see how to cut it. We will set to cut metals. This might need a diamond saw. You may need to cut it with a diamond saw which I don’t have.

  D: Can you do wire EDM?

  M: Potentially, I cannot cut glass. Is this glass?

D: This is glass carbon.

M: Let me do a quick test.

(The machinist was using multimeter.)

M: So it is conductive. So potentially we could cut it using wire EDM. Because when I clamped into the machine, it needs to be grounded. This has to be grounded to the machine.

Observation 9:

- D: I will use sand paper.

  M: File is better. Because for sand paper, you cannot control the angle. Let's go and take a look.

  (The machinist helped the student to modify the part using a file.)

Observation 14:

- M: I would like to get a drill that is specifically for copper. I would like you to buy it.

  D: How much does the tool cost?

  M: It is probably less than 15 dollars.

Observation 16:

- M: So what are you gonna to fasten it? How will you fasten it?

  D: it's gonna be a threaded rod. But we can just use the same threaded rod we used.

  M: Does it have to fasten it? Why I asked it is can we weld it?

  D: No.

M: Does it have to be remote?

D: Yes, it has to be remote at some point.

- M: I have got a guy that know… He does spend many years in aerospace. He is gonna work for me here. He is gonna position very fine weld. He is using the microscope. He does really nice weld. We can even weld it as well.

  D: we could. That is the thing. We previously used rivets. I threaded those. The reason I don't like those is that it couldn't go out without the hole and rivets disassembled. But we can still do that. We can do that for it.

A.1.8 Manufacturability

Observation 2:

- M: So you did this in a CNC, the tool may be chattered or make a lot of noise.
- M: This is the harder part cause this is deep and the chips get caught there (the deep hole).

Observation 12:

- M: For the wire, the problem is that the wire we have is 12 thousand, 10 thousand exactly. But it burns, so it is actually 12 and half thousand. The second thing is you want me to make something really thin, that's we will try on the wire EDM, not the thicker EDM. Right?

  D: I am not sure.

  M: The one on the left is the wire, this one got 10 thousands diameter. The one on the right is the thicker, we use electronic which cut it into two.

D: I am thinking about the wire thing.) M: But the wire is way too big for all of these. Let’s look at this. On a millimeter scale, the wire is .3.

D: So at least 300 micros?

M: Yes, that’s is the diameter of the wire.

D: the wire is accurate, the x, y positioning?

M: Yes, it is very accurate. The other thing, you need to think if this is the wire, let say the wire is this big.

(The machinist draw on the paper to show the radius of the bottom made from wire EDM) (D: It does not matter if here is this shape.)

M: You are going to have the larger radius.

D: Can I have 10 micros here for the x, y position?

M: we can try. I’ve never done it. The first you got to remember it was .0215 close to 300 micros wide with a wire. And overburn. The wire is not that thick, the overburn will be a couple thousand. Therefore, it is going to be 12 thousand.

Observation 14:

- M: You need to remember, (use wire EDM) will give you the radius on the bottom. The wire EDM is .0125 mm, we can do 300 micros.

Observation 15:

- M: It is small, but it is possible. We need to look at the machinability.

Observation 16:

- M: When we weld something, it may lose the perpendicularity. That will be a concern. (D: we will need our perpendicularity for the electric surface.)

- M: I have no concern at all that it goes there 100 thousandths.

A.1.9 Redesign/Part modification

Observation 2:

- M: If this piece is separated, you can get much shorter piece. Even perhaps this feature could be on this part, if there is a way to make this into two pieces.
- M: If you turn the piece to this shape, and then you also have a diameter here you can turn some of the stock off. What can you do with this to make there is an easier way to remove the stock.
- M: So this thing, are they 45 degrees of that? or whatever the degree of it. So you can put something here and something here. So you can rotate that and soldering that. You are adding a feature here. So you can just remove this thing and cut.

Observation 11:

- D: This is the drawings we have last time, so my mistake was I thought the positioning of this can hold this part. But it does not do any of that. It is my fault, communication wise. Do you remember last time that some machinist suggested to use an interference fit? it should hold the position.

  M: Let’s try it. If you want. let’s cut this off, and weld it. Before we do any of this (the new parts). Let’s see if we can practice basically. Because these are already no good. So let’s see if we can take two or three of this or even all of these.

- M: If it does work, we will close it up and start the new parts. If our plan of cutting this away and slide it up. What am I thinking is you know if we can tight them this side (the outside), we can tight them this side (inside).

  D: Is that possible?

  M: We will try.

Observation 12:

- M: If you can go back and draw that, redraw that and give me that width, you can do whatever you want to do. And I can give you a try.

  D: just keep this distance, I will increase the length due to the overburn.

  M: I will give you a try.

Observation 16:

- M: You cannot go any deeper?

  D: You can I guess. We just need that top surface here.

  M: What I am saying here is you are only going 40 thousandths… So if I have 100 thousandths, it gives you 25 thousandths here.

  D: you can do that. I think the issue comes I want to keep it standardized. If you can do it for that, it is fine.

- M: The other thing that is important to you is when we do it, we might want to change the SolidWorks drawing, and update you what we have done. We will email you that.

A.1.10 Quantities of parts

Observation 1:

- D: I have two of this.

Observation 2:

- M: Will you make multiple pieces?

Observation 12:

- M: Are these separate pieces?
- D: Yes, 9 pieces.

Observation 16:

- M: Do you remember how many you need?

  D: as many as we possibly can. So I think at least three of each. Is that okay?

  M:Initially, let's make one of all of them. You go to your lab. If it doesn't work, then we are going to know.

  D: sorry, I forgot, these will be couples. So one inside and one out. So we need six of each.

A.1.11 Tolerance

Observation 5:

- M: I also need to know why you get two decimal places. If you have two decimal places, you tell people it is large. If you have three decimal places, you tell us it is tight. You don't want tight tolerances everywhere. You might need tight tolerances, 3 decimal places here, 3 decimal places here, may be 3 decimal places on your dent. I am not sure where you need them. So that’s why 2 decimal places and 3 decimal places. Does it make sense?

Observation 7:

- M: what is the tolerance of the perpendicular?
- M: What if I tear the tolerance zone of the Teflon?

  D: A tiny bit does not matter

Observation 10:

- M: What is the tolerance?

  D: I don’t know.

A.1.12 Hole

Observation 3:

- M: So are you going to tap both sides of this?

  D: Yes.

  M: And this is for the hinge, right? So actually we will tap this in. so this is dowel pin for hinge.
- M: This should be drilled for hinge. So this won’t this kind. Since you want this can be move back and forth. And this can be drilled clearance for 6-32 correct? Cause the screw can go through it and locked here.
- M: The hole goes all the way through. We could draw hidden line here. Then we could see for sure that it goes all the way through.

Observation 10:

- M: I just want to make sure if it is critical. If yes, we can drill it. You see here (the bottom of the hole) is flat. If we drill, drill has a drill point with 135 degrees. Is it okay or does it need to be flat?

  D: it should be flat. It should be flat bottom to make the spring sit in.

Observation 16:

- M: This is the one we have, no threads?

  D: if you don't have a drawing to do them. Then don't worry about it.

A.1.13 Fixture

Observation 2:

- M: You need a good fixture to do that.

Observation 6:

- M: We need to have something to hold to. So hold here and we can cut it out.

A.1.14 Scale

Observation 3:

- M: What is the scale? Is it 1 to 1? (the machinist use a ruler to measure it). So perhaps 3/8. 0.375 perhaps.

A.1.15 Clearance

Observation 3:

- M: This is gonna look slightly different because this is the side the hinge is and you will cut out a little for the clearance here.
- M: We can always cut more space for the hinging, right? that is the opening. What we can do is before we pin it, we can hold it and place it to make sure.

A.1.16 Unit system

Observation 5:

- M: This is on imperial? (D: Yes) Why do we have 200 thousand, .2?

  D: Some dimensions in mm, some in inches.

  M: Hold it on, that is probably not mm, that will be a really small hole. 0.31mm is really one small hole.

  D: I mean .31 inches converting to mm.
- M: My recommendation is go through and check your drawings. If you want, we probably happy to have a hybrid drawing, that is you have everything in inches, except these two pins. It is acceptable, at least we know this is 6 mm, and this is 8 mm.

A.1.17 Surface finish

Observation 13

- M: You want to polish the back side?

D: I want to sand it smooth in such a way it is flat.

M: What I will probably try to do is going there with a flat cutter, a single point tool, and by doing that, you should be able to get a good surface finish. It should be easy to machine.

A.2 Interview Quotes

A.2.1 Tolerances

Quotes from the designer:

- ‘I give them tolerances and dimensions, how they get there is not important to me.’ [when answering if the interviewee cares about what manufacturing process is chosen.’]

Quotes from machinist 1:

- ‘you can draw this perfect but it can’t be fabricated perfect. Not without a lot of tolerances added to the drawing, a lot of flatness called out, hole diameters….’
- ‘I have people putting 4 decimal places on the whole drawing and they don’t mean anything’

Quotes from machinist 2:

- Tolerance on acrylic and polycarbonate material, called out in ‘tenths’.
- ‘3 decimal is plus minus 5 typically’, ‘DO you want it that close?’ [refers to making tolerance plus-minus 1]
- One decimal place means ‘outside is not critical’. ‘One place is plus-minus 50 thousandths’, ‘2 place is plus-minus 10 thousandths’

- ‘All of our machines machine straight from the model but we still need a drawing to put in the hands of the machinist, so that he knows what the tolerance is.

A.2.2 Dimensions

Quotes from the designer:

- ‘cant really think of any miscommunication, because I know what they’re looking for. I spend a lot of time making drawings accurately, with all the dimensions on it.
- ‘every now and then there’s a dimension that was missing on the drawing. Because I think it was clear, but it wasn’t.’
- ‘I think this is probably the most common situation.’ The designers who actually build this part or actually design this part try to put these in the engineering drawings. It’s very much in your mind what it is and really obviously what these dimensions are. And they just oversee.’ [when asked missing information/dimensions]

Quotes from machinist 1:

- ‘you can draw this perfect but it can’t be fabricated perfect. Not without a lot of tolerances added to the drawing, a lot of flatness called out, hole diameters….’
- ‘outside of the profile does not really matter but all the hole patterns have to match up with something else. They dimension everything off an edge that does not matter and they dimensioned everything off another edge for a different part’ [Proceeds to draw and elaborate about this for another couple of minutes]

Quotes from machinist 2:

- ‘Typically outside dimensions are clear’
- ‘Hole dimensioned from this side to here and another hole dimensioned from this side to here, but what they actually want is the distance between the two holes’

A.2.3 Hole callouts

Quotes from the designer:

- ‘because the drawing didn’t spell it, they could put the hole anywhere [in the orifice plate]’
- ‘if you have to make holes bigger, it’s great, doesn’t quite work the other way.’

Quotes from machinist 1:

- ‘He used the word HOLE and said ¼-20.’ ‘He didn’t say tap ¼-20, he wrote hole.’ ‘If I sent this to the shop, they will drill a hole and tap it for a ¼-20 bolt’ ‘I called him.’ ‘He said, no, no, it should be clearance.’

Quotes from machinist 2:

- ‘Hole size, whether it’s supposed to be a threaded hole or a clearance hole’, ‘If you want to thread, it needs to be smaller’ [talks for about 2 mins about threaded and clearance holes and lack of callouts on drawings]

Quotes from machinist 3:

- ‘Sometimes, they are struggling understanding the difference between external and internal thread.’
- ‘I have to let them understand I can’t do a square hole.’

A.2.4 Surface finish

Quotes from the designer:

- 'material choice, for say like surface finish.'
- 'if it's too rough, there might be some leaks that come out of it.', 'I talked to the company that brazes it and they said its okay'

Quotes from machinist 1:

- 'vendor materials vary'
- 'they pour Plexiglas and it becomes wavy', 'I can machine it but it will lose its transparency'
- 'When you get into chemical coating, we get into major issues because they have not done their homework on the coating they are calling out.

A.2.5 Pin fits

Quotes from machinist 1:

- '….half inch hole for a dowel pin. Is that dowel pin being pressed or is that slip fit for the dowel pin? They don't call that out.' [Talks about how hole dimensions change based on that.]

Quotes from machinist 2:

- Dowel pins: 'Does it need to be slip fit or press fit?'
- You can't get information about pin fits from 3D model and what side they're on.

Quotes from machinist 3:

- ‘They may come to me and say I want this to be a press-fit. How much smaller this should be?’ ‘(I will) stop them, (ask) how much surface contact you are going to have?’

A.2.6 Communication and feedback system between designers and machinists

Quotes from the designer:

- ‘few more occasions where I got some feedback’ ‘because I want to minimize the risk, because that process has some risks associated with it’ , when talking about brazing. ‘Less optimum design from bonding perspective’
- ‘when I review drawings, they point out challenges’, ‘iterative process of feedback’
- ‘structural features because of pressures and so forth and pointing those out and taking images of them.’
- ‘me going over there is limited to something very specific’ , ‘otherwise email is good’ [when talking about how the interviewee deals with manufacturing problems]

Quotes from machinist 1:

- ‘depending on my relationship with customer, if you’re a regular customer, I would be more willing to help and go over your designs’
- ‘I try not to show my frustration, but it comes out sometimes.’

Quotes from machinist 2:

- ‘They don’t tell us how everything fits together’
- ‘Verbal information is good, but if you got detailed stuff, you really need a drawing’
- ‘I’ll draw something and ask “Is this what you want?”’
- ‘I tell them upfront if I can do it or if I can’t’ [Talks about lack of ceramic machining capability]
- Says he can ‘fix most problems on the phone 90% of the time’, otherwise designers can be in shop ‘within 30 minutes’.

Quotes from machinist 3:

- ‘Ours are students working with drawings, and make a request… If you don’t make it face by face, it will be 6 weeks behind.’
- ‘Personally in our shop, on our system online, there is a place the technicians can go up and add comments.’ ‘it is all about documentation, if you don’t document it. It’s he says she said, and then use some misunderstood words.’

A.2.7 Drawings

Quotes from the designer:

- ‘two-step process, where you have to split up your drawings, and spend a good amount of time on both and eliminate a lot of the pitfalls that could occur with one big assembly drawing.’
- ‘ambiguity is still left because this task of taking a 3D CAD model and putting it into a form that is convenient and explicit for a machine shop is very mundane’,

'not necessarily bad because process may force you to think about the design more.'

- '[Drawings] facilitated or allowed the design to be simpler while maintaining its functionality'
- 'might make you careless during design phase, if you don't have to make engineering drawings.'
- Common questions regarding drawings: 'usually I may have left out a dimension', 'copies and pastes part number of fitting onto drawing.', 'sometimes I put too much information on the drawing'
- 'happens more often than not, or rather every now and then' [when asked if he has revised drawings after submitting them to machine shop.]

Quotes from machinist 1:

- 'use whole paper, machinists can't see information on drawing'
- 'People will design in metric and be like, "Hey, just convert it to inches'. Talks about inches and metric for almost 2 minutes
- Third angle and first angle views: 'When you draw in inches, it should be in third angle. When you draw in millimeters, it should be in first angle.
- 'They've gone back and started adding things or changing things' [says this is a trainwreck, in his opinion]

Quotes from machinist 2:

- 'You can draw everything in 2D but it's a little more complex when you start breaking it down.'

Quotes from machinist 3:

- ‘What they are struggling is calling the accurate units.’ ‘Because you have the metric system, and you have the English inch system.’

A.2.8 Need for designers to know manufacturing capabilities and for machinists to know why design decisions were made.

Quotes from the designer:

- ‘certainly not the machine shop, because I kind off know what their capabilities are’ ‘How they get to this doesn’t really matter with me’, when asked if he asks questions about performance variables.
- ‘In some instances that, sort of made it easier if I changed something in the design for them to make have significant benefit and their actual manufacturing process.’
- ‘it’s beneficial for them to think about what it is and what it does and what my constraints are’, ‘eliminates some of the suggestions that they might make if they had not known about the actual physical process.’
- ‘what they need to have to eliminate as much ambiguity as possible’
- ‘concerned about whether or not my design allows them to do whatever they need to do during the assembly stage.’
- Some machinists: ‘People build it, they are just machinists.’ Just follow the drawing, that’s the end of that.’ Good machinists: ‘The good ones, such as the machine shop people or sheet metal people, they try to understand what is going on. I am not sure that it’s something correlated to if they are good at it, they are just generally more, maybe technical interested.’ ‘Or they are just curious to know

what it does; I'm not sure if knowing what it does really helps them build better parts.' '(Maybe) knowing what it does actually helps them understand and makes it more efficient for them to understand the constraints that we are working with.'

Quotes from machinist 1:

- 'you have to think about the process when you design'
- Talks for another 2 minutes about how he can provide the most help if he has all the information about how things go together and what they do ('acryllic machining')

Quotes from machinist 2:

- 'We don't want to be in a liability situation so we try to stay ahead of the curve and try to figure out the application'
- 'Sometimes when they design things, it looks good.' 'But if they would change this feature, if they change that feature, it could go from a 10-hour part to a 2-hour part.'

Quotes from machinist 3:

- 'When you bring in a pawn piece, the first question will be what's the material?' (interviewer answered titanium) 'Why would you make it out of titanium? The next question will be why it is need to be titanium. What specifics requirements telling you that needs to be titanium?'
- 'I'm starting to look into the geometry. You are making this small radius. What is going on here? Is it the strength? Could you angle it out of here so we don't have to go in this corner? You got this weird shape here. It is really hard to turn that.

And we probably had to put that into the CNC tool(?) for a 3D tool pass. It is getting lots of machining. So could we modify the shape at all to make it more easier to machine?'

- 'The more features, the more axis the machines need to have. Or more operations. More sequences. May need to go to three different machines.'

A.2.9 Experience of designers

Quotes from the designer:

- 'designer has to be aware of standards', pressure vessels 'wall thickness'
- 'sometimes when things are done too quickly, there's a fitting that's in the wrong spot…..'

Quotes from machinist 1:

- 'they want to force you to do it on a particular machine, where the precision is not gonna be what they want it to be'
- 'Everything goes back to how experienced you are.'
- 'They don't have any concept that I got to order material…'

Quotes from machinist 2:

- 'Lack of just not knowing..' [talking about material choices]

A.2.10 Design revisions

Quotes from the designer:

- 'costs a lot of money and takes more time, rebuilding it in a modified way was pretty challenging economically and time-wise.'

Quotes from machinist 2:

- '…..sometimes I'm thinking can we change this a little bit? Sometimes yes, sometimes no, its about a 50-50'
- '…it might take an hour or less to machine if I change one feature by 10-thousandths, they're like have at it.'

A.2.11 Additional quotes and information about interviews

The designer

- Spends about a minute talking about how he knows what machine shops are looking for, through his experience.
- Spoke 2-3 times about eliminating ambiguity

Machinist 1

- 'understanding what you can or cannot do in a machine shop.'
- 'We counterbore off the other side'
- Talks for a couple of minutes about flatnesses being an issue, due to material being imperfect when it comes from vendors.

Machinist 2

- Says ‘lack of experience’ a lot. And talks about hole patterns and tolerances 3 times.
- ‘We have [taken jobs without drawings]’
- [Talks or about 3 mins on different types of drawing and CAD software they use]
- Speaks about tolerances a lot.
- Talks about pressure vessel standards. ‘Exotic materials’
- Talks about standards.
- ‘each material is gonna bend a little bit different, gonna stretch a little bit different.’
- ‘They would have their own formulas based on the equipment they have.’

Machinist 3

- Talks about the students don’t know how much time needed to machine a part.
- Talks about 3d printing several times.
- Talks about an example that people keep changing their models.

APPENDIX B. DFM GUIDELINES

B.1 DFM Guidelines for Machining

B.1.1 General guidelines for machining

1. Specify the most liberal surface finish and dimensional tolerances possible, consistent with the function of the surface, to simplify the prime machining operation and to avoid costly secondary operations like grinding, reaming, lapping, etc.
2. Design the part for easy fixturing and secure holding during machining operations. A large, solid mounting surface with parallel clamping surfaces should be provided to assure a secure setup.
3. Avoid designs that require sharp corners and sharp points in cutting tools because these make the tools more subject to breakage.
4. Use stock dimensions whenever possible if so doing will eliminate a machining operation or the need for machining an additional surface.
5. It is preferable in all single-point machining operations to avoid interrupted cuts, if possible, because they tend to shorten tool life or prevent the use of faster-cutting carbide or ceramic tools.
6. Design the part to be rigid enough to withstand the forces of clamping and machining without distortion. The forces exerted by a cutter against a workpiece can be severe, as can the clamping forces necessary to hold the workpiece securely. Parts that may be troublesome in this respect are those with thin walls, thin webs, or deep pockets and deep holes that require machining. Also design the

part so that a rigid cutter can be employed while still permitting access to the surface.

7. Avoid tapers and contours as much as possible in favor of rectangular shapes, which permit simple tooling and setups.
8. Reduce the number and the size of shoulders because they usually require extra operational steps and additional material.
9. Avoid undercuts, if possible, because they usually involve separate operations of specially ground tools.
10. Consider the possibility of substituting a stamping for the machined component. If tooling is available, or if quantities are sufficient to amortize the tooling cost, a stamped-sheet-metal part invariably will be lower in cost than one made by machining, provided of course that the dimensional accuracy and surface finish are adequate for the component's function.
11. Avoid the use of hardened or difficult-to-machine materials unless their special functional properties are essential for the part being machined.
12. For thin, flat pieces that require surface machining, allow sufficient stock for both rough and finish machining. In some cases, stress relieving between rough and finish cuts also may be advisable. Rough and finish machining on both sides is sometimes necessary. Allow about 0.4 mm (0.015 in) stock for finish machining.
13. It is preferable to put machined surfaces in the same plane or, if they are cylindrical, with the same diameter to reduce the number of operations required. When surfaces cannot be in the same plane, they should be located, if possible, so that they all can be machined from one side or from the same setup.

14. Provide access room for cutters, bushings, and fixture elements.
15. Design workpieces so that standard cutters can be used instead of cutters that must be ground to a special form.
16. Avoid having parting lines or draft surfaces serve as clamping or locating surfaces. Provide alternative clamping and locating surfaces if possible.
17. Avoid projections, shoulders, etc., which interfere with the overrun of a cutter. Instead, provide clearance space at the end of the cut. The space can be cast or formed to minimize machining. This also can provide a noncritical space for burrs.
18. Burr formation is an inherent result of machining operations. The designer should expect burrs, provide relief space for them, if possible, and furnish means for easy burr removal.
19. The design should incorporate standard tool geometry at diameter transitions, exterior shoulders, grooves, and chamfer areas.
20. The design should minimize unsupported, delicate small-diameter work when possible to reduce work deflection from the cutting tool. Keeping parts as short as possible will help in this regard. Short, stubby parts are easier to machine than long, thin parts, which require tailstock or steady-rest support.
21. A product design that requires an irregular and interrupted cutting action should be avoided when possible. Hole intersections, curved or slant surface drilling, and hole or slotting operations before turning are illustrations of this condition.

22. When castings or forgings are designed with large shoulders or other areas to be faced, the surface should be 2 to 3° from the plane normal to the axis of the part. Such an incline provides edge relief for cutting tools.
23. Radii, unless critical for the part's function, should be large and conform to standard tool nose-radius specifications. Often, the radius can be left to manufacturing preference.
24. Specify a break of sharp corners where sharpness or burrs may be hazardous or disadvantageous to the function of the part. The product design should be specific in this regard; i.e., do not specify "Break all corners" unless this is really necessary, because such operations are quite costly. Sharp corners and burrs can be minimized if chamfers or curved surfaces are placed at the intersection of other surfaces. Often such curves or chamfers can be included in a casting or forging at no extra cost before machining.
25. The design of the product must be such that parting lines, draft angles, and forging flash are excluded from surfaces used in the clamping or locating of the part.
26. When a part is to be tracer-turned, the turned contour should be such that easy tracing is possible with a minimum number of changes of stylus and cutting tool. Grooves with parallel or steep sidewalls are not feasible in one operation, and undercuts should also be avoided.

B.1.2 *Guidelines for drilling*

1. The drill entry surface should be perpendicular to the drill bit to avoid starting problems and to help ensure that the hole is in the proper location.
2. The exit surface of the drill also should be perpendicular to the axis of the drill to avoid breakage problems as the drill leaves the work.
3. If straightness of the finished hole is particularly critical, it is best to avoid interrupted cuts unless a guide bushing can be placed at each reentry surface. If the drill intersects another opening on one side, some deflection will occur. Even when straightness is not critical, it is important that the center point of the drill remain in the material throughout the cut to avoid extreme deflection and possible drill breakage.
4. It is best to use standard drill sizes whenever possible to avoid the added cost of special drill grinding.
5. Through holes are preferable to blind holes because of easier clearance for tools and chips, especially when secondary operations such as reaming, tapping, or honing are required.
6. When blind holes are specified, they should not have flat bottoms. The preferred drill bit generates a pointed hole, and if other bottom shapes are specified, secondary operations are required. Square-bottomed holes also cause reaming problems because reamers have tapered ends and require room for chips to fall if tool wear and breakage are to be avoided.
7. Avoid deep holes (over 3 times diameter) because of chip-clearance problems and the possibility of deviations from straightness. Note that while extremely deep

holes (e.g., gun barrels) can be drilled, they require different tooling, equipment, and techniques (see "Gun Drilling and Gun Reaming" below). They are not necessarily costly if gun-drilling is available but nevertheless constitute a special operation and for this reason should be avoided if possible.

8. Avoid designing parts with very small holes if the small size is not truly necessary, because small drills are more susceptible to breakage. About 3-mm (1/8-in) diameter is a desirable minimum for convenient production.
9. If large finished holes are required, it is desirable to have cored (cast-in) holes in the workpiece prior to the drilling operations. This saves material and reduces the power required for drilling.
10. If the part requires several drilled holes, dimension them from the same surface to simplify fixturing.
11. Rectangular rather than angular coordinates should be used to designate the location of drilled, reamed, and bored holes. They are easier and more nearly foolproof for the machinist to use in laying out the part or a drill fixture.
12. Insofar as possible, design parts so that all holes can be drilled from one side or from the fewest number of sides. This simplifies tooling and minimizes handling time.
13. Design a part so that there is room for a drill bushing near the surface where the drilled hole is started.
14. Standardize the size of holes, fasteners, and other screw threads as much as possible so that the number of drill spindles and drill changes can be minimized.

15. When production quantities are large enough to justify multiple-drilling arrangements, the designer should bear in mind that there are limitations as to how closely two simultaneously drilled holes can be spaced. Smaller holes can be spaced more closely than larger ones because gearing, chucks, and bushings can be smaller. As a rule of thumb for small holes of 6-mm (1/4-in) diameter or less, spacing should not be less than 19 mm (3/4 in), center to center, although in some cases 13 mm (1/2 in) is possible.

B.1.3 Guidelines for milling

1. The product design should permit the use of standard cutter shapes and sizes rather than special, nonstandard cutter designs. Slot widths, radii, chamfers, corner shapes, and overall forms should conform to those of cutters available off the shelf rather than those which require special fabrication. Specialized form-relieved cutters are costly and difficult to maintain.
2. The product design should permit manufacturing preference as much as possible to determine the radius where two milled surfaces intersect or where profile milling is involved. This will permit the use of standard available or most easily ground cutters.
3. When a small, flat surface is required, as for a bearing surface or a bolt-head seat perpendicular to a hole, the product design should permit the use of spotfacing, which is quicker and more economical than face milling.

4. When spotfaces or other small milled surfaces are specified for castings, it is good practice to design a low boss for the surface to be machined. This simplifies machining and paint removal and usually results in a less sharp edge.
5. When outside surfaces intersect and a sharp corner is not desirable, the product design should allow a bevel or chamfer rather than rounding. Bevels and chamfers may be created by face mills, whereas rounding requires a form-relieved cutter and a more precise setup, both of which are most costly to maintain.
6. Similarly, when form-milling or machining rails, it is best not to attempt to blend the formed surface to an existing milled surface because exact blending is difficult to achieve.
7. Keyway design should permit the keyway cutter to travel parallel to the center axis of the shaft and form its own radius at the end. A standard cutter should be able to form both the width and end radii of the keyway slot. This principle also applies to other slots, saw cuts, and shell and face milling.
8. A design that requires the milling of surfaces adjacent to a shoulder or flange should provide clearance for the cutter path. Small steps or radii or inclined flange or shoulder surfaces should be used.
9. A product design that avoids the necessity of milling at parting lines, flash areas, and weldments will generally extend cutter life.
10. As with other surface-machining processes, the most economical designs are those which require the fewest separate operations. Surfaces in the same plane or at least in the same direction and in parallel planes are preferred.

11. Milling operations often can be performed more economically if the product design lends itself to stacking so that a milled surface can be incorporated into a number of parts in one gang-milling operation. This also can occur if parts can be "sliced" from a long workpiece after the milling operation. Even if the parts do not have flat adjoining surfaces as shown, provided they are designed so that they can nest together, gang milling may then be employed.
12. The product design should provide clearance to allow the use of larger-size cutters rather than small cutters in order to permit high material-removal rates, more efficient use of machine horsepower, and lower dynamic operating conditions when machining. Smaller-sized cutters are less rugged and require higher operating speeds to machine effectively. They are more subject to vibration, chatter, and deflection of tool and machine components. Large clearances also facilitate the use of carbide-insert cutters. These provide high production rates, minimal cutter maintenance, and less frequent downtime for tool changes.
13. In end-milling slots in mild steel, the depth should not exceed the diameter of the cutter.

B.1.4 Guidelines for reaming

1. Even though it is good practice to ream with a guide bushing when the hole location or alignment is critical, do not depend on reaming to correct location or alignment discrepancies unless the discrepancies are very small.
2. Avoid intersecting drilled and reamed holes if possible to prevent tool breakage and burr-removal problems.

3. If a blind hole requires reaming, good practice calls for extra drilled depth to provide room for chips.

B.1.5 Guidelines for boring

1. Even when boring operations are employed, avoid designing holes with interrupted surfaces. Interrupted cuts tend to throw holes out of round and cause vibration and tool wear.
2. Avoid designing holes with a depth-to-diameter ratio of over 4 or 5:1; otherwise, accuracy may be lost owing to boring-bar deflection. (If carbide boring bars are available, depth-to-diameter ratios of 8:1 are feasible.) If deep holes are unavoidable, consider the use of stepped diameters to limit the depth of the bored surface.
3. Use through holes whenever possible. If the hole must be blind, allow the rough hole to be deeper than the bored portion by an amount equal to at least one-fourth the hole diameter.
4. Remember that except for small quantities of special-diameter holes, boring is more expensive than drilling and reaming. Equipment is more costly, and the operation is slower. Use boring only when the accuracy requirements demand it. Do not specify bored-hole tolerances unless really necessary.
5. With boring as with other precision machining operations, the part must be rigid so that deflection or vibration as a result of cutting forces is avoided. Care also must be taken in the workpiece and fixture design to avoid deflection of the part

when it is clamped in the fixture, for if this occurs, machined surfaces will be off location when the part springs back from its clamped position.

B.1.6 Guidelines for planing, shaping and slotting

1. Since the cutting forces in planing and shaping may be abrupt and rather large, design parts so that they can be easily clamped to the work table and are sturdy enough to withstand deflection during machining.
2. It is preferable to put machined surfaces in the same plane to reduce the number of operations required. (This stricture does not apply if a multitooled planer can machine both surfaces simultaneously.)
3. Avoid multiple surfaces that are not parallel in the direction of reciprocating motion of the cutting tool because this would necessitate additional setups.
4. Avoid contoured surfaces unless a tracer attachment is available, and then specify gentle contours and generous radii as much as possible.
5. With shapers and slotters it is possible to cut to within 6 mm (1/4 in) of an obstruction or the end of a blind hole. If possible, allow a relieved portion at the end of the machined surface.
6. For thin, flat pieces that require surface machining, allow sufficient stock for a stress-relieving operation between rough and finish machining, or, if possible, rough-machine equal amounts from both sides. Allow about 0.4 mm (0.015 in) for finish machining. Then finish-machine on both sides.
7. The minimum size of holes in which a keyway or a slot can be machined with a slotter or shaper is about 1 in.

8. Because of a lack of rigidity of long cutting-tool extensions, it is not normally feasible to machine a slot longer than 4 times the hole diameter (or the largest dimension of the opening).

B.2 DFM Guidelines for FDM

1. Avoid simple parts. Considering different manufacturing processes if
   a. The part is the same shape as common stock materials, or is completely 2D;
   b. The part is mostly 2D and can be made in a mill or lathe;
2. Use FDM if the part curvature is complex (splines or arcs) for a machining operation such as a mill or lathe.
3. Use FDM if there are interior features or surface curvature is too complex to be machined.
4. FDM parts are light and medium duty. Considering different manufacturing processes if mating surfaces are bearing surfaces, or are expected to endure for 1000+ of cycles.
5. Considering different manufacturing processes if mating surfaces move significantly, experience large forces, or must endure 100-1000 cycles.
6. Use FDM if mating surfaces move somewhat, experience moderate forces, or are expected to last 10-100 cycles.
7. Use FDM if surfaces are purely non-functional or experience virtually no cycles.
8. The support structure can ruin surface finish. Avoid support structure if not necessary.
9. Use support structure for overhang features, unsupported features will drop.

10. Avoid thin features since they will almost always break.
11. Major structure elements such as walls, interlocking features should be thicker.
12. Minimum wall thickness for FDM parts varies depending upon the slice thickness that will be used to build the part.
13. Consider stress concentration of the interior corners. Use generous chamfers, fillets and/or ribs to transit the interior corners gradually.
14. Mating parts should not be the same size. Proper clearance should be given between mating assembly parts to prevent them from fusing together. The standard guideline for creating clearances on assemblies being produced fully assembled is a minimum Z clearance of the slice thickness. The X/Y clearance is at least the default extrusion width based on a suggested minimum wall thickness. The minimum clearance needed for mating parts, when not producing the components fully assembled, is equal to the tolerance of the FDM machine itself.
15. Avoid large, flat areas since they tend to warp.
16. Avoid producing hollow parts with a "watertight" interior. The support material cannot be removed.
17. Make sure the opening to the part interior are of sufficient size to remove support material.
18. Holes (those in bosses as well) on an FDM part are generally fractionally undersized. When tight tolerances are required, holes will be drilled or reamed to ensure the diameter is accurate.
19. When designing built-in threads, avoid sharp edges and include a radius on the root. Sharp edges can be stress concentrators in plastic parts. Creating an ACME

thread design with rounded roots and crests has been found to work well when using FDM. Also, use a “dog point” head of at least 1/32 in. (0.8 mm). This dog point design makes starting the thread much easier. Small threads produced from the FDM process are not recommended and not possible for holes or posts smaller than a 1/16 in. (1.6 mm) diameter. An easy alternative is to use a tap or die to thread holes or posts.

20. Because FDM is an additive process, undercuts for design features such as O-ring grooves are easily handled without causing manufacturing issues.
21. Draft is unnecessary in FDM parts.
22. extruded plastic has its strongest strength in the tensile mode along the x-y plane. Since the layers are held together by “hot flow” across the strands (one strand is cooling while the other is laid upon it), the lowest strength is in the Z-direction for both tensile and shear modes.
23. Overhanging non-supported features, such as the top of a closed box, require a foundation of support material to be built, which increases build time and material usage. Because of this, build orientation is usually determined by the part processor. For example, half of a box-shaped casing will be built with the main exterior facing down, so that no internal support is needed.
24. Parts may be sectioned (prior to manufacturing) in CAD. Sectioning can be used to:
    a. Build parts that are too big for the build chamber (cut parts into sections).
    b. Eliminate excessive amounts of support structure.

c. Cut overhanging features from the top of the part (in its build orientation) and build separately.

d. Preserve fragile features that may be damaged in post processing.

e. Section fragile features from the part and build them separately. (Once fragile features are removed they can be built in an orientation that produces a stronger part. There are a number of bonding methods to reattach features and join sectioned parts.)

25. When using fastening hardware, use a cap screw or a flanged cap screw. The flat surface eliminates multidirectional stresses from cracking the part. Washers can also be used to spread the load over the largest possible surface area. Lock nuts, embedded nuts, or metal inserts are all stronger fastening options than adding threads to the FDM plastic.

26. Many times, the design of FDM parts can be solid rather than using a hollowed-out design supported by bosses and ribs. This can reduce build time and use less support material. It is not necessary to reduce wall thickness of a boss, rib, or gusset in FDM parts. Generally, bosses can be the same size as the part thickness or up to 0.02 in. (0.5 mm) less. It is also important to use gussets or ribs to support the bosses in FDM parts. This will increase the amount of stress the feature can withstand.

27. Minimum suggested text size on the top or bottom build plane of a FDM model is 16-point boldface. Minimum suggested text size on vertical walls is 10-point bold. In most cases the supports generated to support text on a vertical wall can be eliminated to save time and material.

Since the FDM process uses engineering-grade thermoplastics, the parts produced are capable of withstanding a number of post-manufacturing processes, including machining operations such as drilling and tapping, sawing, turning, and milling. (Note that heat is easily built up in plastic parts, so removing the material slowly and using coolant keeps the part from distorting.) Other post processing operations may include smoothing, burnishing, sealing, joining, bonding, and plating.

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